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STUDY OF PERFORMANCE IN A REVOLVING SPACE STATION SIMULATOR AS A FUNCTION OF HEAD ROTATION ABOUT Y AND Z CRANIAL AXES

FINAL REPORT

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GENERAL DYNAMICS
Convair Division

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ON A STUDY OF PERFORMANCE IN A REVOLVING SPACE STATION SIMULATOR AS A FUNCTION OF HEAD ROTATION ABOUT Y AND Z CRANIAL AXES

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GENERAL DYNAMICS
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FOREWORD

This document is the final report on a study conducted by Convair division of General Dynamics for the NASA Manned Spacecraft Center. This final report is submitted in full compliance with the requirements of Contract NAS9-5232 under the National Aeronautics and Space Administration Manned Spacecraft Center Procurement and Contracts Division, Houston, Texas.

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SUMMARY

The engineering parameters needed for design of a rotating spacecraft with maximum habitability are:

a. The maximum angular velocity to which a crew can satisfactorily adapt.

b. Minimum radius of rotation for satisfactory crew performance.

c. Optimum physical orientation and position of the crew, and most efficient arrangement of consoles, displays, and controls.

d. Stability requirements (perturbation tolerances) for the various radii and angular velocity combinations.

The objective of this study contract has been to develop data pertinent to item c. The experiments were designed to compare and determine which types of head rotation are least disturbing to performance of a human subject experiencing an artificial gravitational field.

CONCLUSIONS. The following conclusions were drawn as the result of this study:

a. Head motions out of the plane of spin become quantitatively more disorienting as the interplanar angle approaches 90°.

b. Y-axis (nodding) head turns are significantly easier than comparable Z-axis (side-to-side) head turns in an environment rotating at a highly stressful rate.

c. Adaptation to such a rate appears to take place rapidly for those head turns performed near the plane of spin, but becomes increasingly more difficult as the interplanar angle increases. Though 45° out of the plane of spin appears to be tolerable for Y-axis head movements at the spin rate used in this study (12.2 rpm), it appears to be unacceptable for Z-axis head movements.

d. Study results suggest that a console operator in a rotating space station can perform without perceptual-motor decrement — even prior to any adaptation to the environment — if he is positioned facing toward or against the direction of spin and his head turns restricted to all-nodding motions within a ± 45° range from the plane of spin. No constraints are required for hand-arm motions. Side-to-side (Z-axis) head motions usually will be in a plane normal to the spin plane — the orientation of maximal stress. Prior to adaptation to the space vehicle spin, some performance decrement may be entailed in deviations from the above constraints. However, rapid operator adjustment — even to the involvement of Z_{90} head turns (i.e., Z-axis turns 90° out of the spin plane) — will often prevent decrement in precision perceptual-motor tasks prior to physiological adaptation.

SIGNIFICANCE FOR MANNED SPACEFLIGHT. If rotation is used to provide an inertial force within a spacecraft, proper orientation of displays and controls should be provided, especially during the period of adaptation to the rotation.

In space, the spinal (Z) axis of the crewman will be in the plane of spin (aligned with the centrifugal vector) much of the time. The Z-axis head movements will then be in a plane 90° out of the spin plane — the movements shown to be most disorienting. The displays and controls to be used during the first few days of rotation should, therefore, be arrayed in the apparent vertical dimension so that Y-axis or nodding motions can be favored in monitoring.

The envelope for monitoring requirements can probably be plus or minus 45° from center (spin plane) on either the leading or trailing bulkhead when vertically arranged displays are used.

RECOMMENDATIONS FOR CONTINUED STUDY. The head rotation and reach envelope studied here were done on a vehicle with a constant angular velocity. Spacecraft will not necessarily have the required stabilization system for a stable platform — either during rotation or static orientation. The "off-nominal" situation is of particular interest because this is when response is most critical.

Studies similar to the one completed but using sinusoidal and random oscillations during static and revolving modes of the MRSSS operation should be conducted to determine the magnitude of the perturbation problem.

SECTION 1

INTRODUCTION

1.1 BACKGROUND. A question of major concern during the 1965 Symposium on "The Role of Vestibular Organs in the Exploration of Space"(1) was the applicability of data from simulators and vestibular studies performed in the one-g earth environment(2, 3) to the situation of a rotating spacecraft in a null gravity condition. In the space situation, the position and alignment of the upright crewman are such that his spine is parallel with the centrifugal vector and in the plane of spin. Though it is possible to build a revolving space station simulator so the resultant gravito-centrifugal vector is parallel to an upright subject's spine, within practical design it is not possible to have his spine simultaneously parallel to the spin plane.

In the rotating spacecraft situation, motions of the head about the Z (spinal) axis (head-turning movements) when the crewman is erect will be movements that are nearly perpendicular to the plane of spin. Such movements will cause maximum labyrinthine Coriolis accelerations.(4) In contrast, head movements about a Y (side-to-side) axis (head-nodding movements) can vary from being in, to 90° out of, the plane of spacecraft spin. Loret(5) suggested that this orientation contrast may well dictate the placement of displays and controls in the aritificial gravity spacecraft, but little effort had been made to quantitatively investigate this important concept. The requirement existed for experimentation to provide design engineers with normogravic data that can be reasonably extrapolated to spacecraft now being considered for long-term missions.

Gray, et al., collected observations from three subjects who were exposed to 1 or 3 g at a 50-ft radius while being rotated in a gimballed gondola at various angles to the centrifuge axis.(4) The authors performed an excellent mathematical analysis of the possible effective torques which might have been generated in the subjects' semicircular canals by the cross-coupled rotations, but the data collected were not of an objectively quantitative nature. Though it was statistically apparent that the reported oculogyral illusions increased in those orientations expected to cause the greatest Coriolis accelerations in the semicircular canals, Gray cautioned that the otoliths were also being affected by different accelerations in the various maneuvers. In the space situation, linear accelerations will maintain an essentially constant direction and provide a nearly constant stimulus to the otoliths, thus reducing the relevance of Gray's data to construction of design envelopes.

Stone and Letko(1) did a series of studies in which they had men do a simple task that required either turning the head (about Z axis) and/or nodding the head (about Y axis) while tying supine and being rotated in a centrifuge. In these studies, the spine was in the plane of spin, but not aligned with the resultant force. Both head motion planes were 90° to the plane of spin, orientations where maximum stimulation would be expected. However, the rapid recycling of the head turns in this study may have prevented all but a minimal cupular deflection to occur. To define design constraints it is necessary to investigate the full stress range to be encountered in the environment. In space, horizontal displays will require monitoring motions 90° to the spin plane but vertical arrangement may be from 0° to 90° out of that plane.

Loret(6) suggested that the correlation between simulation on earth and the space situation might be assessed if a simulator could be provided with a centrifuge arm sufficiently long that a tolerable spin rate would provide one g radially, and with the simulator floor at 45° from the g vector. Then by reclining a subject in a chair at 45° to the simulator floor it would be possible to position his Z axis in the plane of spin (with his head toward the spin axis), or at right angles to the plane of spin (with his feet toward the center of rotation), as seen in Figure 1-1. In any position, his Z axis would always be displaced from the gravito-centrifugal resultant by 45°, providing a constant otolith stimulus in all head turn planes.

The Convair Manned Revolving Space Station Simulator (MRSSS), which is an 8-ft by 14-ft by 7-ft room mounted on a large centrifuge (Figure 1-2), was capable of providing such an environment and the experiment was performed on a preliminary basis(7) in a Convair-funded study. Subjects were required to turn their heads through 70° and immediately perform a psychomotor test on RATER (acronym for Response Analysis Tester). Results of the tests are shown in Figure 1-3. A steady decrease

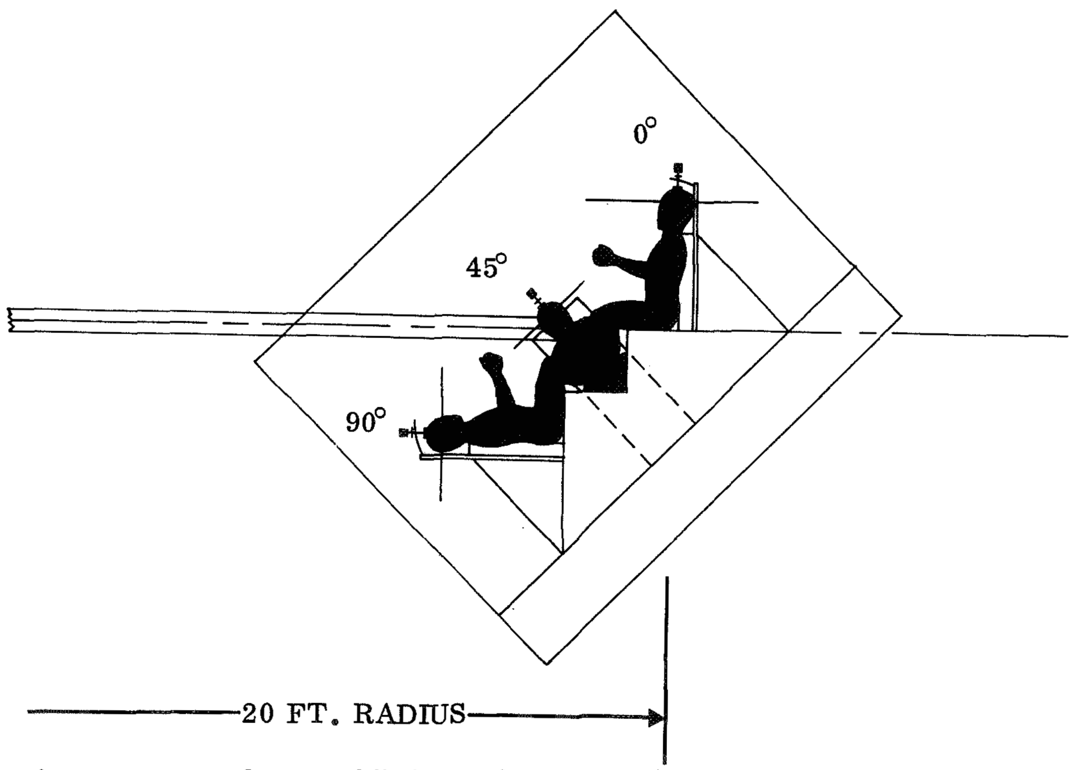


Figure 1-1. Relation of "Plane of Head Turn" to Plane of Spin (MRSSS Inclined at 45° at 12.2 rpm)

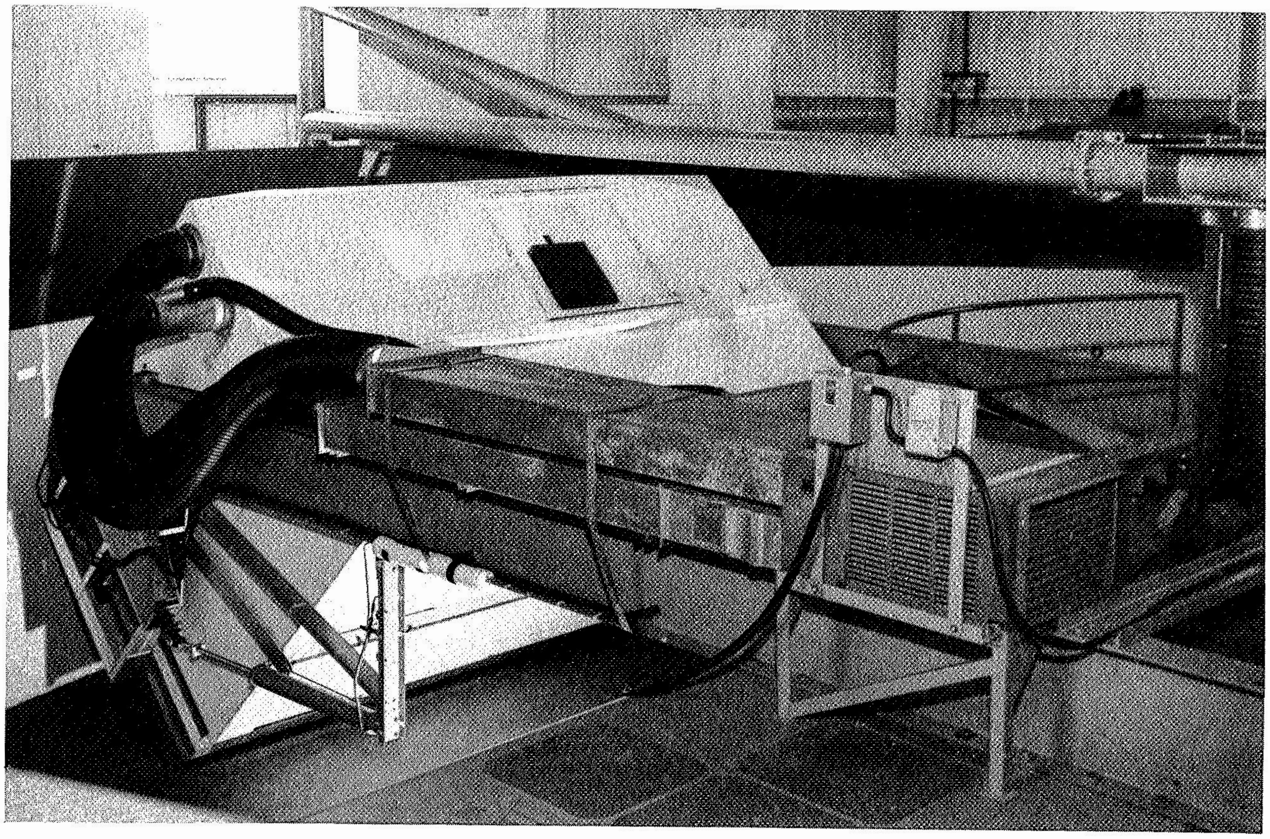


Figure 1-2. Manned Revolving Space Station Simulator

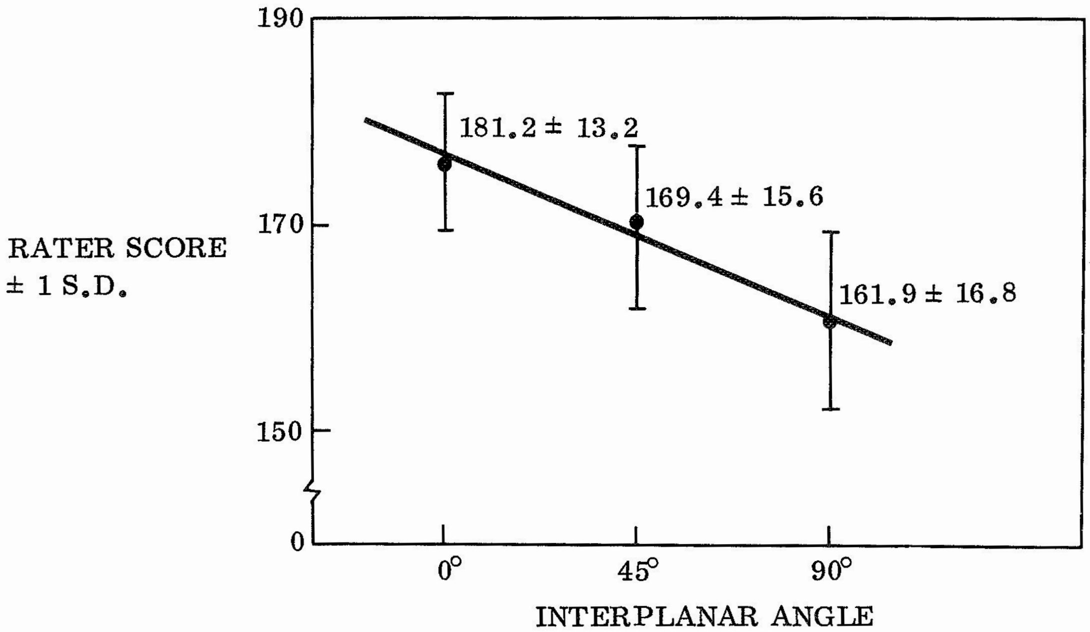


Figure 1-3. Performance as a function of the Angle Between Head-Turn Plane and Spin Plane

in performance ability occurred as the angle between the plane of head rotation and the plane of simulator spin increased. This function agreed with earlier concepts about such an environment but did not provide enough information for design, since it concerned only Z-axis head movements.

1.2 CURRENT STUDY. In July 1965, a proposal was made to the National Aeronautics and Space Administration to conduct a study aimed toward more adequate definition of the optimal orientation of the spacecraft crew for best perceptual-motor performance. This proposal led to the current study under Contract NAS9-5232. The study was broken into two tasks.

Task I was the testing of 24 subjects on perceptual-motor performance involving head rotations about the Z axis (spine) and about the Y axis (through the ears) while being spun in the MRSSS. The two types of head rotation (turning and nodding) were measured and compared on the same subjects for 0°, 45°, and 90° orientations of the planes of head rotation (about Z and Y axes) relative to the spin plane. In this report the axis of rotation and the interplanar angle (i.e., the angle between the head-turn plane and the spin plane) are designated Z_0, Z_{45}, Z_{90}, and Y_0, Y_{45}, and Y_{90}.

Task II was done to establish the physiological mechanisms responsible for the results obtained in Task I and to determine the significance of the observations on control tasks during exposure to a high angular velocity.

1.2.1 Objectives. The objectives of the present study were to extend the technique developed during the Convair-funded study to accomplish the following:

a. Compare the disorientations resulting from head turning (Z-axis movements) with those from head nodding (Y-axis movements).

b. Quantify these disorientations as a function of the angle separating the plane of head turn from the plane of spin.

c. Explore the feasibility of adaptation to head movements in these various orientations.

d. Investigate the mechanisms leading to the performance degradation.

e. Apply the information derived to spacecraft habitability and control-display arrangement, and determine the possible effects that the favored display would have on control activities requiring reach movements.

1.2.2 Method. As in the preliminary, Convair-funded study, the spin rate of 12.2 rpm at the twenty-foot radius provided one g radially; the floor of the simulator was inclined 45° from its static horizontal which aligned the gravito-centrifugal resultant at right angles to the simulator floor. In this study, however, a chair was constructed to incline the subject 45° on his side (Figure 1-4) rather than on his back. This

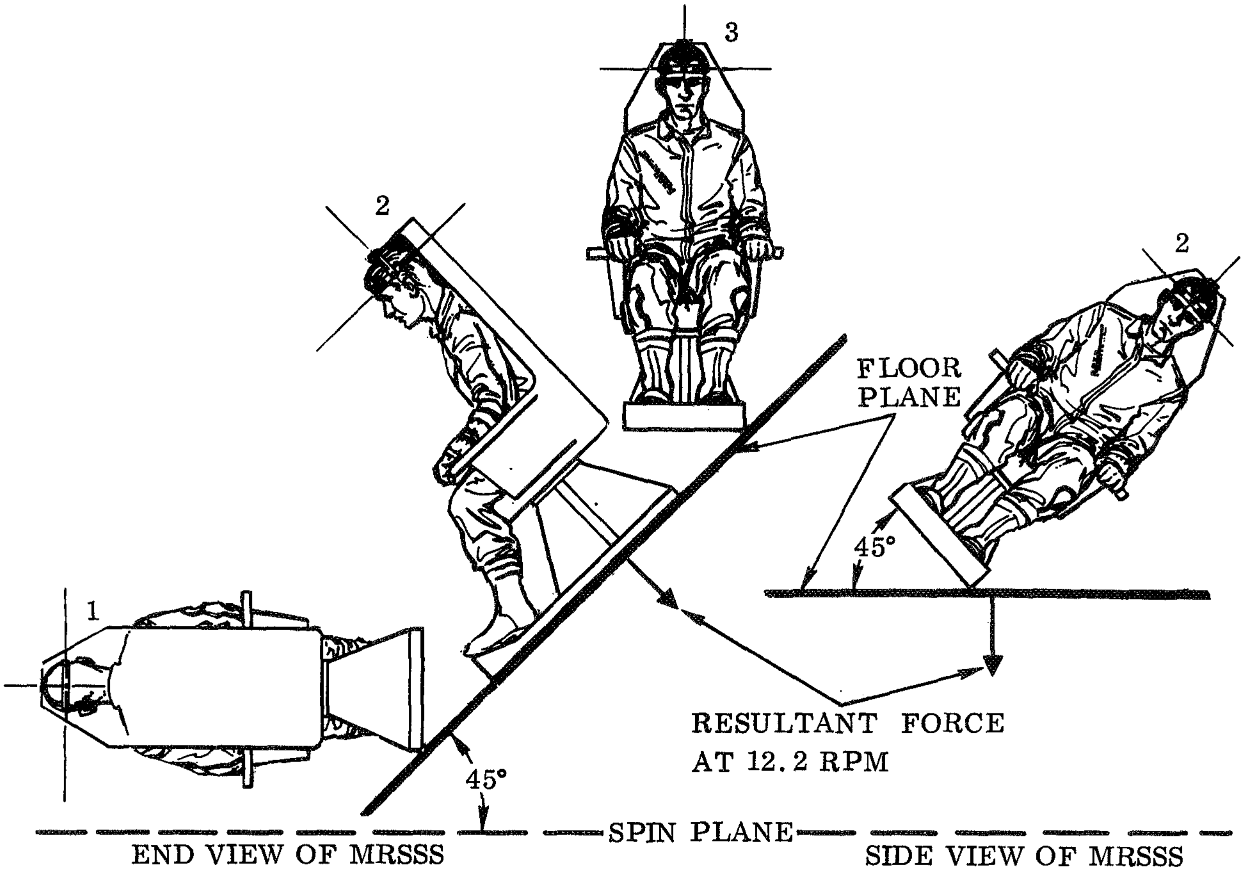


Figure 1-4. Orientation of Subjects in MRSSS

position still maintained his Z axis at a constant angle of 45° from the inertial resultant for any chair orientation. With the subject facing the direction of centrifuge spin (position 1 in Figure 1-4), head turns about the Z axis were perpendicular to the spin plane (creating maximum Coriolis effect), while head turns (or nods) about the Y axis were in the plane of spin (creating minimal Coriolis effect). When he faced against the direction of spin (position 3 in Figure 1-4) the opposite was true: Y-axis turns were 90° out of the plane of spin and the Z-axis turns were in the plane. Halfway between, when facing the spin axis (position 2 in the figure), both his Z- and Y-axis head turns were 45° from the plane of spin. Orientation angles for the various subject positions shown in Figure 1-4 are summarized in Table 1-1.

Table 1-1. Orientation Angles as Functions of Subject Position

SUBJECT ORIENTATION TO MOTION	POSITION	BETWEEN SPINE AND RESULTANT	BETWEEN HEAD TURN PLANE AND SPIN PLANE	
			Z AXIS	Y AXIS
Forward	1	45°	90°	0°
Backward	3	45°	0°	90°
Toward Center of Rotation	2	45°	45°	45°

Figure 1-5 shows the inclined chair and the head restraint system used in this study. Head motions were restricted to exact planes by use of a double ball-bearing circular race for the Z-axis motions, an adjustable sleeve-bearing for the Y-axis motions, and stops for both degrees of freedom. A number of adjustments were available — and needed — to provide full ease of head movement, especially in Y-axis movements.

Anthropometric differences greatly affected the point of Y-axis rotation and there was also considerable difference in the way the head was nodded. Some subjects used most of the cervical area in the motion, others flexed primarily at the atlanto-occipital joint. It was found that both Y and Z turns had to be completely comfortable for the subject or he fatigued quickly. Figure 1-6 shows the adjustments required to accommodate the range of body types represented by the subjects.

Both the Y- and Z-axis turns were recorded by a Grass polygraph from potentiometers mounted at the centers of axis rotation. Readouts were calibrated prior to testing each subject.

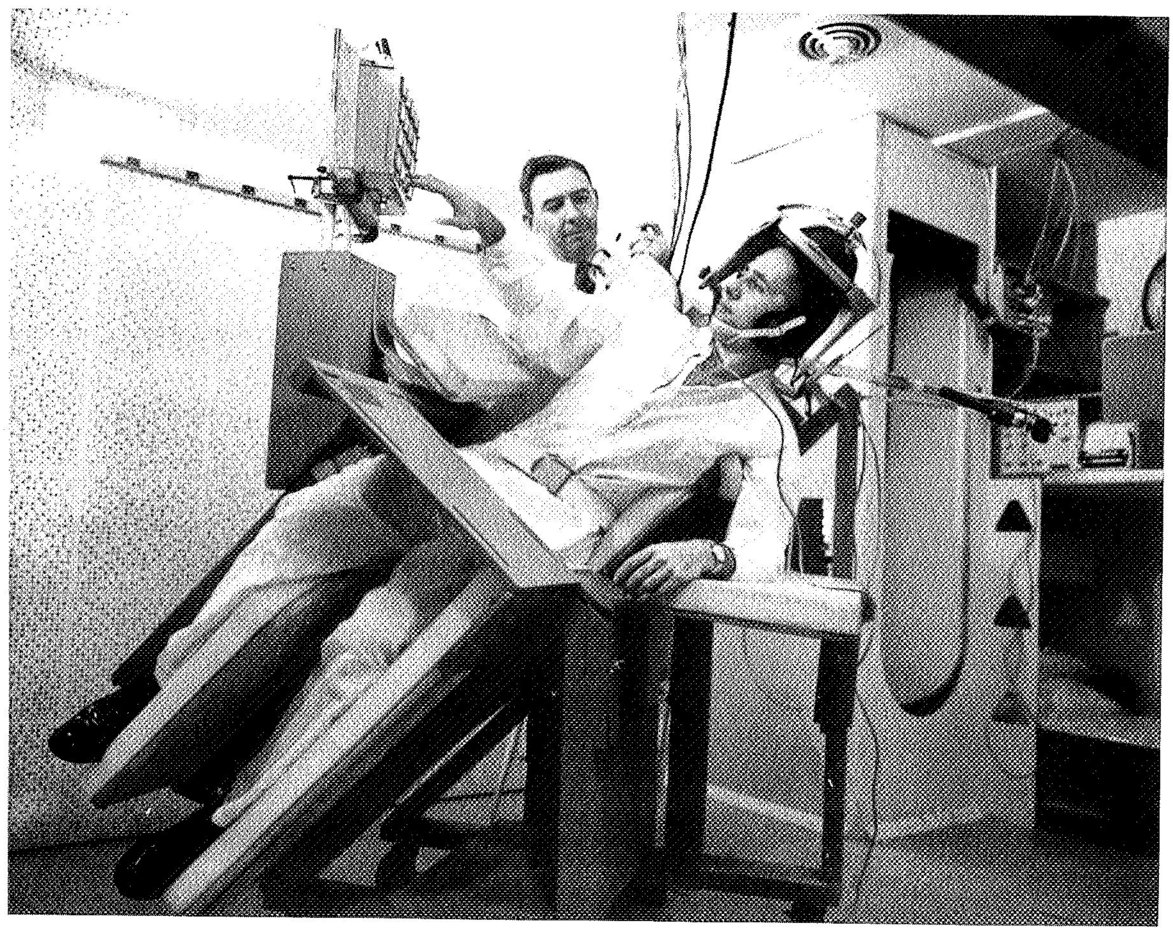


Figure 1-5. Inclined Chair and Biaxial Head-Turning Restraint

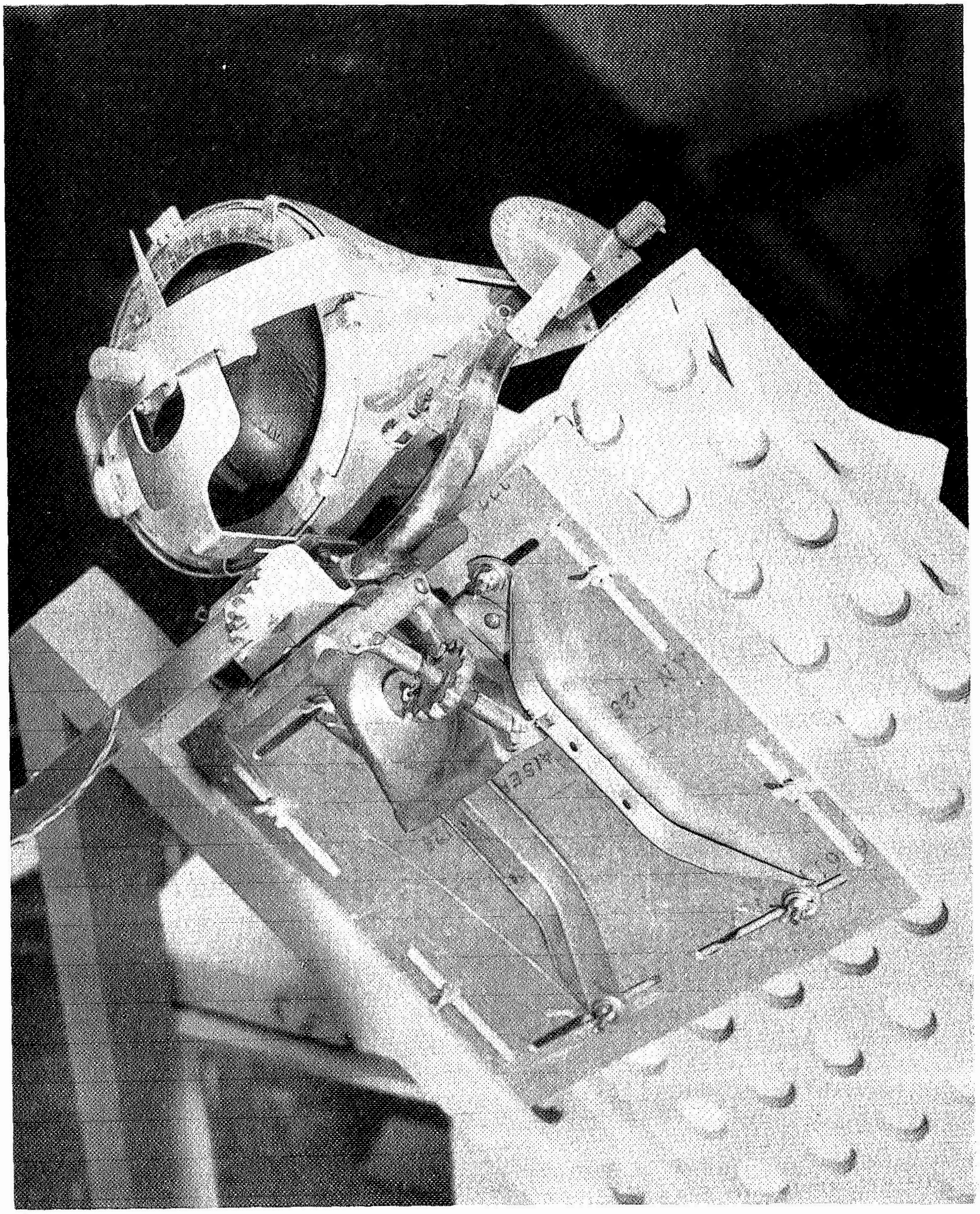


Figure 1-6. Head Restraint Adjustments

SECTION 2

TASK I — PERFORMANCE AS A FUNCTION OF HEAD TURNS DURING ROTATION

One experiment was conducted under Task I. In this experiment, 24 subjects were tested for performance of perceptual-motor tasks, following head turns about the Y and Z cranial axes during rotation in the Convair MRSSS, as a function of the inter-planar angle between the plane of head turn and the plane of vehicle spin.

2.1 PROCEDURE. The apparatus used to measure performance of each subject after each head turn was the Logical Inference Tester (LOGIT)[8] which is shown in Figure 1-5. The subject's console contains twenty buttons, each of which lights when pressed. This console is connected to the test administrator's console, permitting the test administrator to program the sequence in which the buttons must be pushed in order to illuminate the entire panel. When the buttons are pushed in the correct sequence the lights stay on, but if an error is made, those lights out of proper sequence go off when a sequentially preceding button is eventually pushed. This informs the subject an error was made and provides clues as to its correction. There are several ways the LOGIT can be utilized. For this experiment, only one sequence was used. The subject was required to memorize this sequence and to become proficient in its repetition prior to the static baseline test. This usually required about one hour.

The subject was then placed in the chair and trained for another 30 minutes using the complete test format. A starting light was placed in a position that required the subject to make a 70° head turn about either the Y or Z axis. The light was on his left for the Z-axis turns, or above his head for the Y-axis turns. Between each LOGIT trial, the subject was instructed to immediately return his head to the starting-light viewing position.

Previous tests in the MRSSS had indicated the importance of allowing adequate time for cupular recovery when attempting to measure disorientation due to head motions.[7,9] Consequently, each orientation test sequence consisted of ten 15-second trials separated by nine 20-second rest periods. Performance was graded on the total number of buttons pressed in proper sequence during the 150 seconds of testing at each orientation.

There were six orientations (0°, 45°, and 90° for Z and Y head turns). After the first three sequences (either Z or Y) were completed, the simulator was stopped and necessary adjustments made to convert the head turning restraint to the other axis. The three sequences for each axis took about 45 minutes, so the subjects were at 12.2 rpm for a total of 1 hour and 30 minutes.

Each orientation could be expected to have an effect on the tolerance to the succeeding head turn sequences. To null this effect, each subject performed a different permutation of orientations. The number of subjects was dictated by the number of major permutations of the two axis movements and three head turn angles to the plane of spin. The 24 test permutations required 24 subjects; each permutation was represented by one subject. Tests were conducted three days a week, and two subjects were tested each day.

Navy jet pilots were used as subjects, to provide a sample that was reasonably homogeneous and qualitatively similar to spacecraft personnel. To simplify chair construction, only right-handed subjects were used. They varied between 25 and 40 years of age and were all active aviators. The motivation and cooperation of the group was exceptional in all cases. Subjects were instructed to avoid turning their heads to the point of overt motion sickness. Whenever they felt that one more head turn might initiate vomiting, they skipped that trial and took a zero score. Using this approach, twenty-four subjects were able to complete all six orientations, and all but five completed all trials. The onboard test conductor and offboard test monitor exchanged positions to limit personal exposure to 45 minutes at one time, or 1 hour and 30 minutes per day, at the 1.4 g resultant. This was done as a precaution because of the small amount of information available on tolerance to repeated exposure to plus g along the Z axis.[23]

2.2 RESULTS. All but one subject felt the Y-axis movements were easier than the Z-axis movements in all orientations. The one subject who felt there was no stress difference between the Y and Z axes showed higher scores for the Y-axis orientations than for the Z. All subjects were able to correctly rate the disorientation for the increasing angle between plane of head turn and spin plane for both Y and Z axis.

Figure 2-1 shows the number of buttons pushed in correct sequence for an average 15-second test trial for all Y- and Z-axis head motions during static and perrotatory testing. The scores are overall means for 24 subjects and the standard error (S.E.) of each mean is shown. The subjective feelings are substantiated by the consistently higher scores obtained in all orientations for the Y axis.

The mean overall head-turn time for all subjects in each orientation is shown in Figure 2-2. Head-turn time (the time required to turn the head 70°) was calculated from the polygraph traces. Again, the Z-axis turns appear to be much more of a stress. For Z_{90} turns, the Z-axis time is dramatically increased to almost twice its static value, while Y-axis turns show a lesser time increase.

Figure 2-3 demonstrates the rapidity with which adjustment to the stresses of certain head turns occurs. Each 150 seconds of testing in each of the six orientations was divided into ten separate trials. When these trial performances are plotted it is seen that the Y axis movement at the 45° orientation appears to be close to the limit for

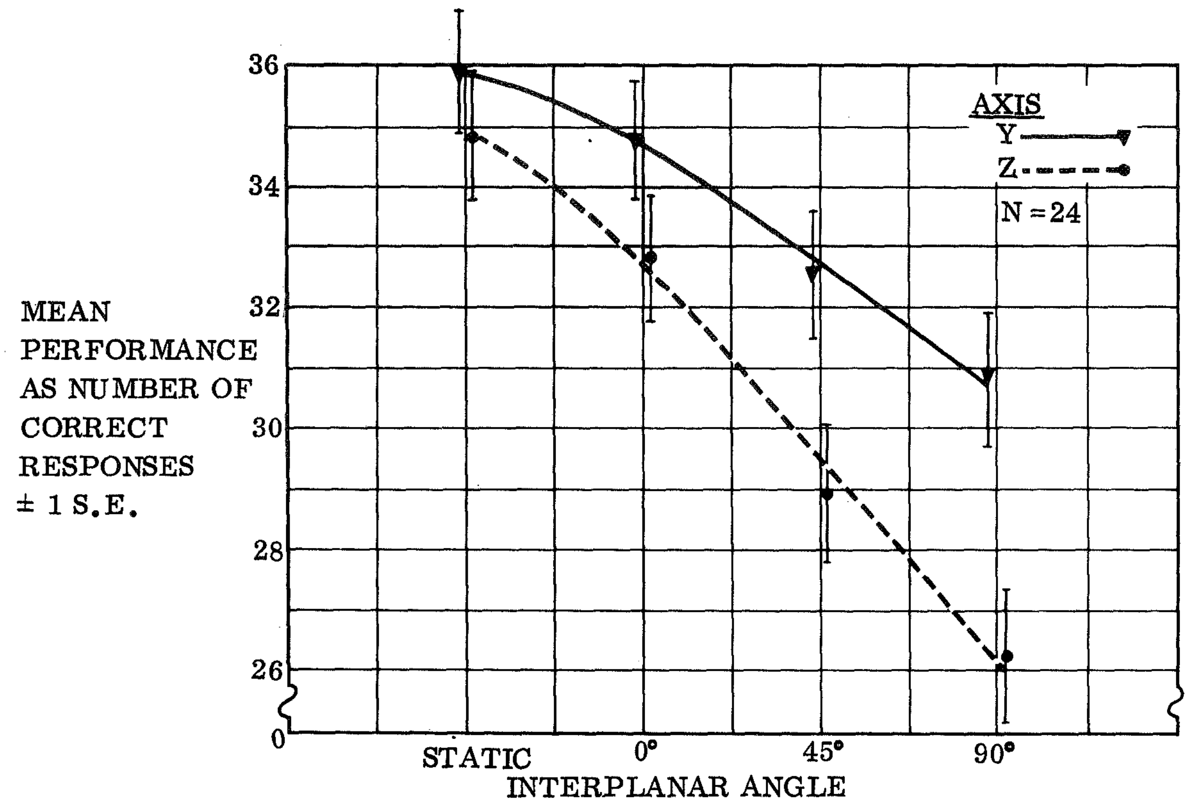


Figure 2-1. Performance as a Function of Interplanar Angle

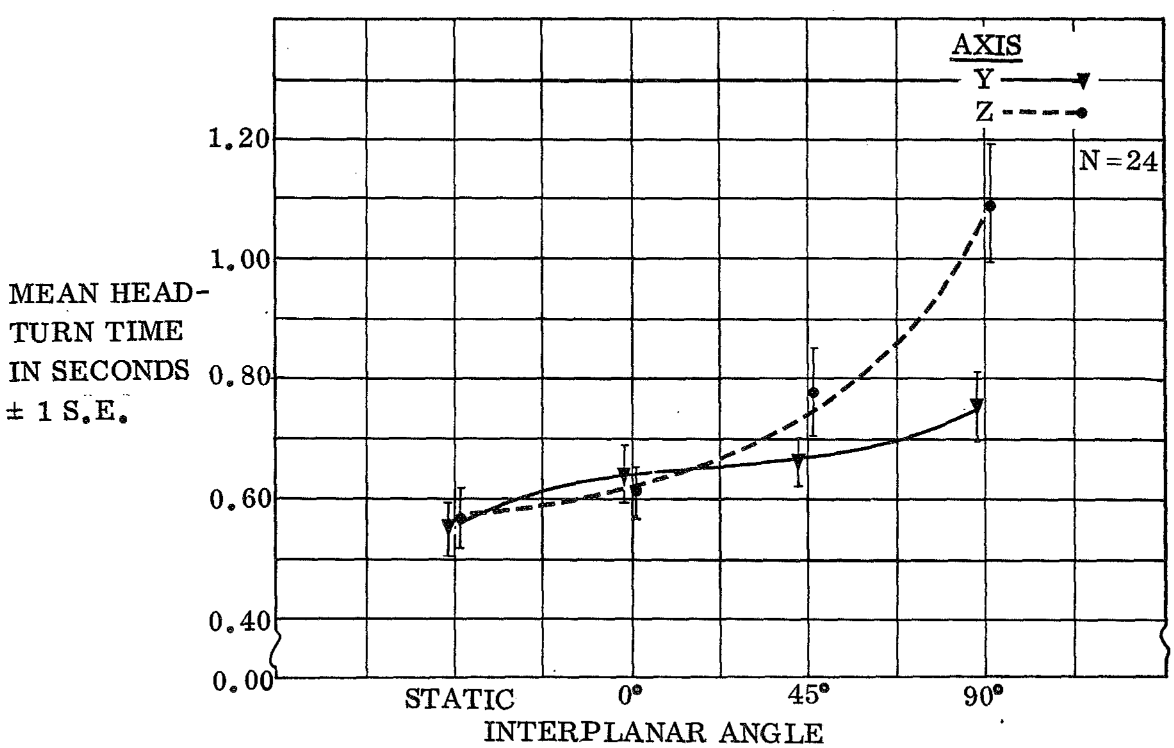


Figure 2-2. Head-Turn Time as a Function of Interplanar Angle

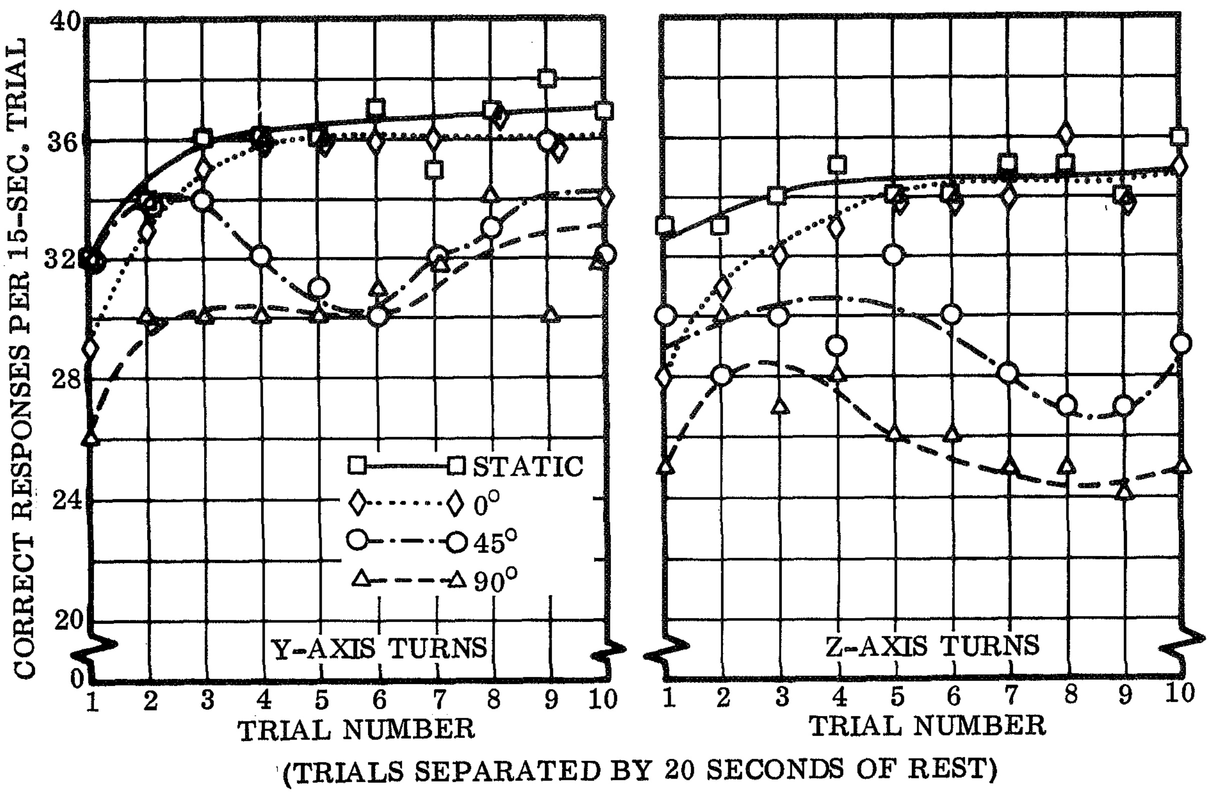


Figure 2-3. Performance Change Upon Repeated Head Turns

adaptation for this length of time. Little improvement occurs during the Y_{90} test, and Z-axis head turns show progressive degradation in both 45° and 90° positions. Inability to make a head turn or to start the trial was scored as a zero; this occurred more frequently with the Z-axis turns than with the Y sequences.

Table 2-1 shows the significance of the differences observed in performance and head-turn time as a function of the turn orientation to the spin plane. $P \leq 0.05$ was considered significant.

Table 2-1. Analysis of Variance of Results

Orientation vs. Performance Efficiency for 24 Subjects			
Within Y Turns		Within Z Turns	
$Y_{45} < Y_S$ *	$P < 0.01$	$Z_{45} < Z_S$ and Z_0	$P < 0.01$
$Y_{90} < Y_S$ and Y_0	$P < 0.01$	$Z_{90} < Z_S$ and Z_0	$P < 0.01$
$Y_{90} < Y_{45}$	$P < 0.05$	$Z_{90} < Z_{45}$	$P < 0.05$
Between Y and Z Turns			
$Z_0 < Y_S$	$P < 0.05$	$Y_{90} < Z_S$	$P < 0.01$
$Z_{45} < Y_S$ through Y_{45}	$P < 0.01$	$Y_{90} < Z_0$	$P < 0.05$
Orientation vs. Head Turn Time for 24 Subjects			
$Z_{90} >$ all others,	$P < 0.01$		

*S = static

SECTION 3

TASK II — MECHANISMS AND APPLICATIONS

Task I results indicate that a significantly greater performance decrement can be anticipated for Z_{90} head turns than for Z_0 head turns. The difference between these orientations is that which has been pointed out as the artifact in the simulation studies done by both Graybiel, et al.[2], and Newsom, et al.[19], in their respective simulators rotating below 6 rpm. In those studies, the Z-axes of upright subjects were oriented at almost 90° to the spin plane, resulting in Z-axis head turns nearly in the plane of spin, rather than at right angles to it as would be the case in an artificial-g space station. Z-axis head turns, therefore, may be anticipated to cause more operational problems than have been suggested in the rotation-tolerance literature to date. Though this problem potential should be significant only prior to adaptation, a better understanding of the mechanisms involved is important.

Task II experiments were designed to learn more about these mechanisms. Physiological reactions observed and the techniques used to study them are pertinent to future space experiments. The testing could be duplicated in a space laboratory, with the comparison of the resulting performance to this study's results providing an assessment of the operational value of normogravic testing. Indirectly, the entire aspect of the gravity artifact could be more clearly defined, providing a more reliable basis not only for artificial-g design, but also for the hypogravic design.

3.1 EXPERIMENT 1: RELATION BETWEEN OCULAR RESPONSE AND PERFORMANCE DEGRADATION. Experiment 1 of Task II was performed to investigate the relationship between ocular response and performance degradation due to head turning in a rotating environment. It appears from the performance results of Task I that a 45° angle from plane of rotation at 12.2 rpm is acceptable for head-turn planes about the Y axis, while 90° Y-axis turns and 45° and 90° Z-axis turns result in significant disorientation, performance degradation and nausea. Subjects frequently complained about blurring of vision and an inability to focus on test buttons. The purpose of this experiment was to further define the design envelope suggested in Task I by measuring the oculographic responses to the same range of head turns. The same rotation rate and test chair used in Task I were used in Task II. A Response Analysis Tester (RATER) was used instead of the LOGIT to measure performance. The RATER[8] shown in Figure 3-1 tests correct rote responses to lights of four different colors or test symbols. The subject responds to each color by attempting to press the correct one-of-four buttons on a console for that color light. When the correct button is pressed the next color appears. Total responses and correct button responses are recorded automatically.

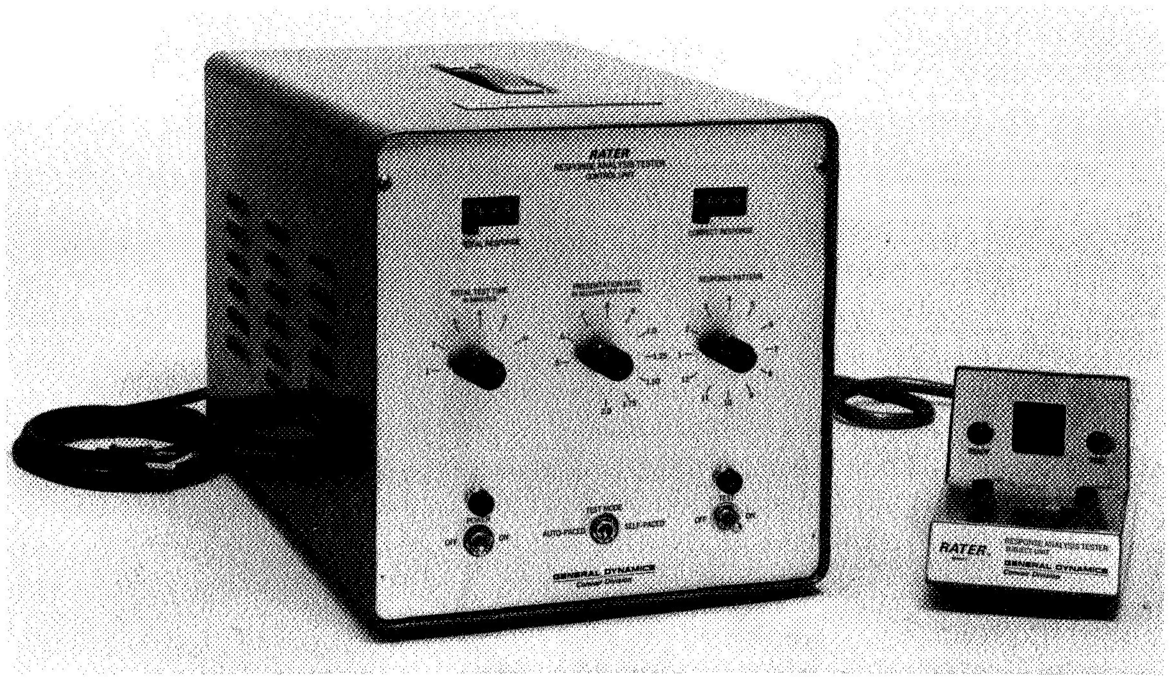


Figure 3-1. Response Analysis Tester (RATER)

For oculogram recording a point source display was required. The basic RATER was modified by installing remote buttons and collimating the light to present a one-degree visual angle. The arrangement is shown in Figure 3-2. The basic Task II sequence totaling 150 seconds of testing consisted of ten 15-second trials separated by 20-second rest intervals. The beginning of each 15-second trial was signaled by a light to the subject's left (Z-axis test) or above his head (Y-axis test). To view the RATER color display the subject then executed either a Y- or Z-axis 70° head turn. Electro-oculograms were recorded on each head turn for both horizontal and vertical components, and results correlated with RATER scores for each head turn orientation. Permutations of orientation presentations were balanced, as in Task I, to null out cumulation artifacts, but the number of permutations was reduced to 12.

3.1.1 Method. The techniques developed in Task I with the inclined chair were used with the RATER as a performance test. This test provides a point of fixation for the subject. The subject responds to four colored lights by pressing the appropriate button to obtain the next signal; the following factors were involved:

a. Lights: red, green, blue, yellow.

b. Test sequence of 10 trials of 15 seconds each, separated by 20-second rests while monitoring for next start signal.

c. At signal, subject turned head 70° to fix collimated display light.

d. Recording of scores included: 1) total response, 2) errors, 3) response latency, 4) head-turn rate.

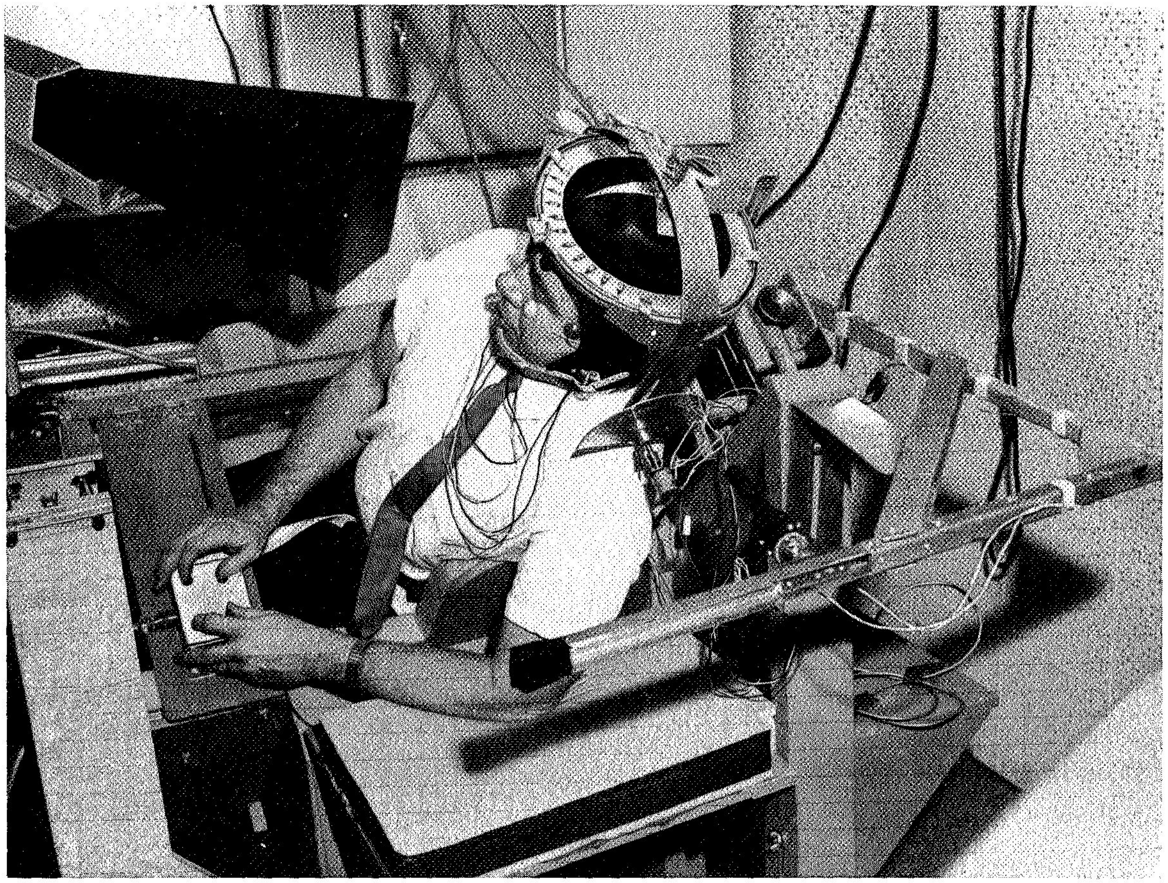


Figure 3-2. RATER Modification for Oculographic Study

e. Oculograph a-c recordings of the vertical and horizontal eye movements were made with five leads for analysis of duration, rate, velocity, and amplitude.

f. Recorder speed: 5mm/sec, running at 100 μV/cm amplification; Beckman bio-potential electrodes were used.

g. Data analysis including correlation of various oculographic parameters with the performance scores at the various orientations of the head turns to the plane of spin. The sequences of orientation were as follows:

SUBJECT NO.	ORDER 1	2	3	4	5	6
1	Z_0	Z_{45}	Z_{90}	Y_0	Y_{45}	Y_{90}
2	Y_0	Y_{45}	Y_{90}	Z_0	Z_{45}	Z_{90}
3	Z_{90}	Z_{45}	Z_0	Y_{90}	Y_{45}	Y_0
4	Y_{90}	Y_{45}	Y_0	Z_{90}	Z_{45}	Z_0
5	Z_{45}	Z_0	Z_{90}	Y_{45}	Y_0	Y_{90}

SUBJECT NO.	ORDER 1	2	3	4	5	6
6	Y_{45}	Y_0	Y_{90}	Z_{45}	Z_0	Z_{90}
7	Z_{90}	Z_0	Z_{45}	Y_{90}	Y_0	Y_{45}
8	Y_{90}	Y_0	Y_{45}	Z_{90}	Z_0	Z_{45}
9	Z_{45}	Z_{90}	Z_0	Y_{45}	Y_{90}	Y_0
10	Y_{45}	Y_{90}	Y_0	Z_{45}	Z_{90}	Z_0
11	Z_0	Z_{90}	Z_{45}	Y_{45}	Y_{90}	Y_0
12	Y_0	Y_{90}	Y_{45}	Z_{45}	Z_{90}	Z_0

h. Twenty male college students with ages between 21 and 28 served as subjects. Two subjects were tested each day: one in the morning, the other in the afternoon.

3.1.2 Results. RATER total score is based upon the total correct responses minus the total incorrect responses for a unit test period, which in this experiment was 150 seconds (10 trials of 15 seconds each). Though the RATER differs radically from the perceptual-motor testing device used in Task I (the LOGIT), the ratios of performance efficiency, seen in Figure 3-3, when comparing all interplanar orientations (both within a given Y or Z turn axis or between turn axes) demonstrate a marked similarity. As in Task I, performance efficiency in 45° and 90° interplanar relationships show progressively increasing decrement as the angle increases, with the Z-axis turn being significantly more intolerable, Z_{45} and Y_{90} of comparable stress, and Y_{45} of marginal effect. It is interesting to note that for the third consecutive, though differing, experimental format (including the company-supported prototype study and Task I) the ratio of performance decrement from Z_0 to Z_{90} to decrement from Z_0 to Z_{45} is 1.6.

Inspection of electro-oculographic records and estimations of total number of degrees of eye movement during the standard test period of 150 seconds indicate several factors of interest. A substantially greater amount of eye movement (lack of eye fixation) occurs during Z-axis turns compared with Y-axis turns, such being true even in interplanar orientations of minimal stress. This marked increase in eye movement during Z-axis head turns is almost entirely the result of the increase in the horizontal component of eye movement as shown in Figure 3-4. Leading eye movement (LEM)[9] appears to be present to a dramatic degree in Z-axis turns, and there is a significant increase in volitional cyclic movements of the gaze as the subject encounters situations of increased disorientation. Nystagmoid movements show an increase in the more stressful Z movements but directly account for only a small percentage of total eye movement. Indirectly, however, the causal relationship appears to be nystagmus producing disorientation resulting in large cyclic excursions of the gaze as the subject

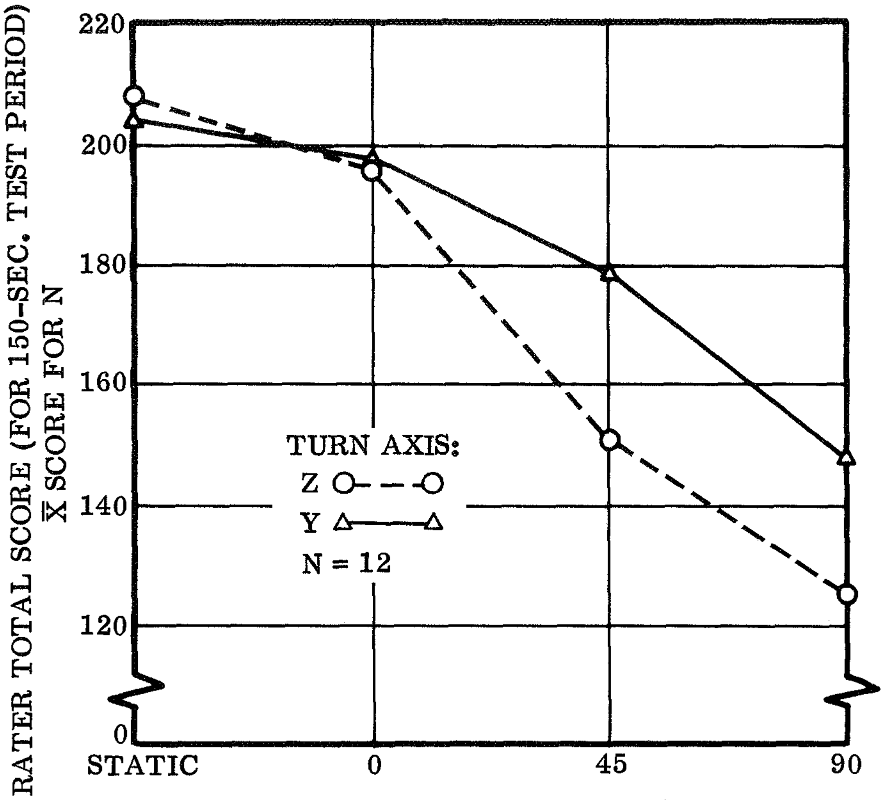


Figure 3-3. RATER Performance as a Function of Subject Turn Axis and Orientation

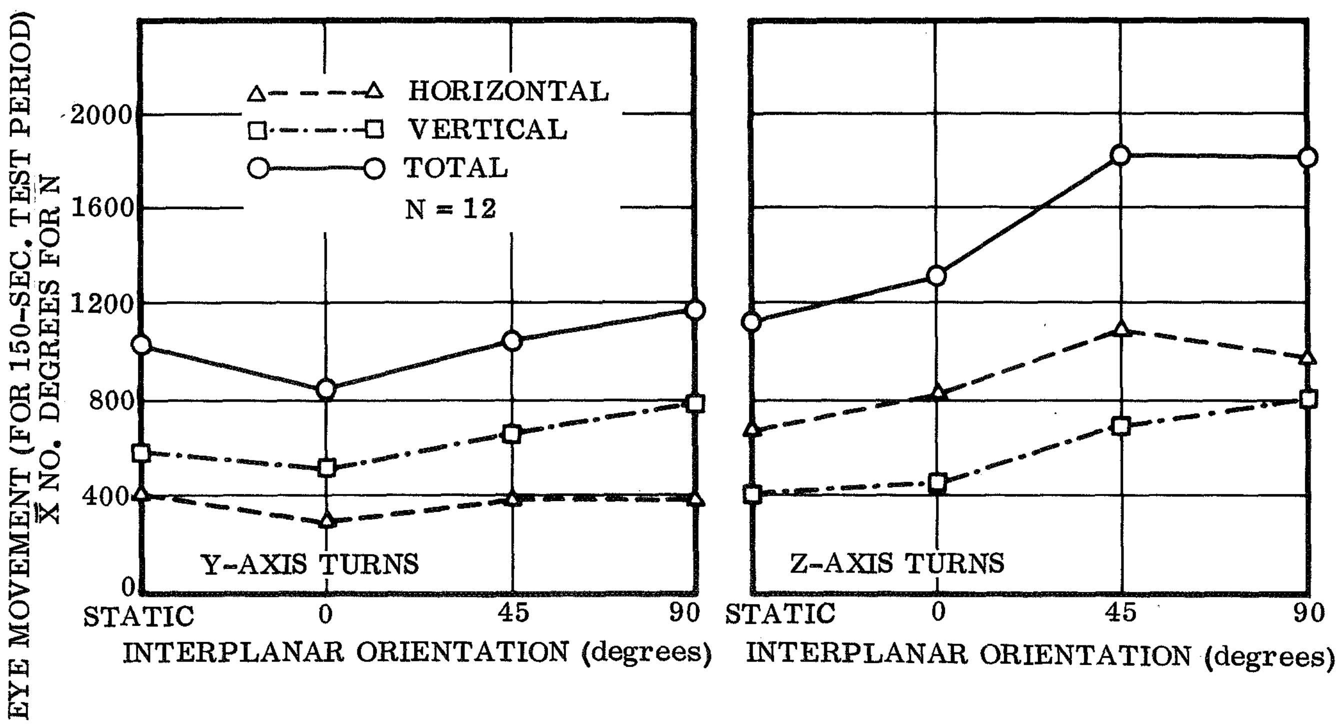


Figure 3-4. Eye Movement as a Function of Subject Turn Axis and Orientation

struggles to fixate on the target light. In all testing during rotation of the simulator (including the least stressful 0° orientation), there is a decrease in the low-amplitude, high-frequency autokinetic movement seen in the static baseline testing. This is partially responsible for the decrease in total vertical eye movement during the orientation, but is insufficient to completely compensate for movement in all other perrotatory testing. Whether this decrease in autokinetic eye movement is due to greater fixation effort in the more stressful hypergravic environment or rather the result of the dominance of other, more intense, oculomotor activity can only be conjectured.

Typical electro-oculographic records are shown in Appendix B, Figures B-1 through B-6. Rapid attenuation of nystagmus due to fixation on the target light was consistently observed. Nystagmus is not so quickly extinguished as the subject returns to await the signal of the cue light (this is shown in the recording in B-6), a fact correlating consistently with the subjective comments of greater disorientation and discomfort as the turn-from-task was executed. This occurs in spite of an allowed and significant decrease in head-turn rate during this return maneuver. Because of the marked and consistent attenuation of nystagmus, due to visual fixation during testing, further reduction of the nystagmographic data was not attempted.

3.1.3 Requirements for Additional Study. Experiment 1 of Task II demonstrated that the decrements in performance and total eye movement are both correlated with magnitude of interplanar angles. The physiological mechanism of performance decrement, however, is not defined by that total eye movement, since the decrement does not appear to be due to blurring from nystagmoid motion. Indeed, the nystagmus observable in the rest position disappears during fixation on the display. To define the eye movement as the limiting parameter it is necessary to have a more direct approach, such as photography, to determine where the subject's eyes are gazing while he is trying to focus on the target light.

3.2 EXPERIMENT 2: PROBLEM OF VISUAL-FIXATION. Results obtained in Task I and in Task II, Experiment 1 of this study suggest at least two related factors of primary importance to the determination of the performance limits of the human operator in a rotating environment. The first is the progressive increase in performance error as the plane of involved head turn is increasingly canted relative to the plane of environmental spin, with pitching (Y-axis) head turns resulting in less error than comparable yawing (Z-axis) head turns.

The second factor suggests a possible perceptual-motor mechanism contribution to the performance degradation. Visual acuity required for optimal performance necessitates adequate retinal stabilization of the display image. This stabilization must be produced by the appropriate oculomotor responses to the synergic vertibular and optokinetic signals. Figure 3-5 (composed of readouts from Task II, Experiment 1) is representative of data from this study. A strong, positive correlation is depicted between performance

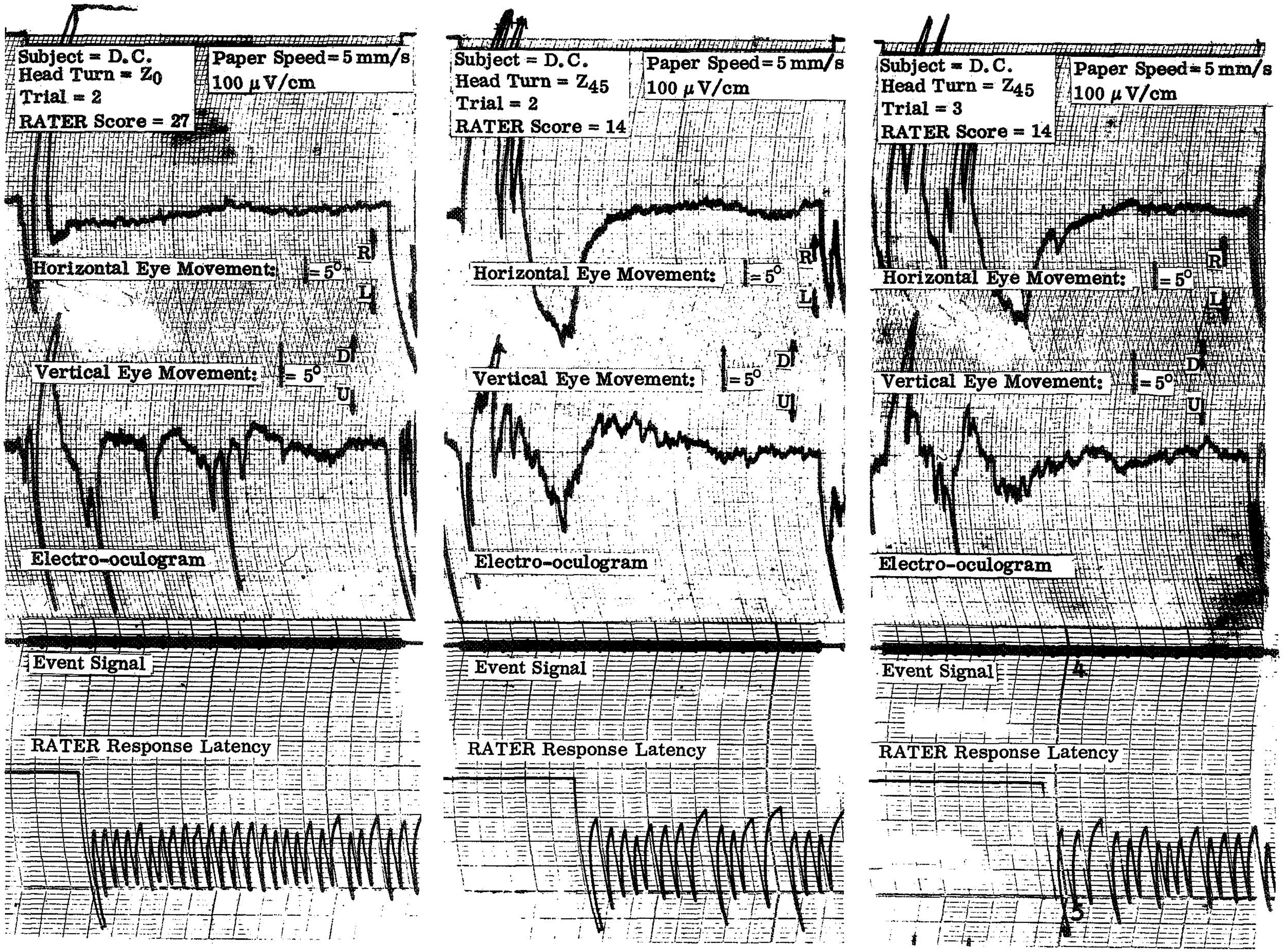


Figure 3-5. RATER Response Latencies and Electro-oculographic Recordings Indicate Difficulty in Visual Fixation

degradation and the difficulty in stabilizing vision following a stressful head turn. The readouts combine the electro-oculograms and RATER response latencies for each of three trials for a single subject: the first for a minimal-stress head turn (Z_0), and the last two for stressful (Z_{45}) turns. For the unstressed turn the oculogram indicates an initial eye movement toward the target display, followed by a rapid stabilization of eye position correlating with a series of correct responses beginning 2 1/2 seconds after the start signal was given. (Each downward deflection of the RATER response latency trace indicates a correct response.) In contrast, the two stressed trials demonstrate a marked aperiodic oscillatory response of the eyes to the head turn that is not clearly nystagmoid in configuration. These intervals of pendular eye movement coincide with hiatuses in scoring at the beginning of each trial.

In the preceding experiments of this study it was seen that not only was there little display of classical nystagmus following the head turns toward the task, but that the increased total eye movement recorded following stressful Z-axis turns, when compared to comparable Y-axis turns, was almost completely due to the horizontal component of eye movement. This is not in agreement with the predominantly rolling (X-axis) nystagmus that would be predicted to occur, and which was essentially the only nystagmus that did occur, though to a minor extent.

The preceding observations suggest that what might be contributing significantly to the oculomotor embarrassment following the stressful head turns is a phenomenon variously referred to as leading eye movement (due to its phase advancement relative to head movement), the anti-compensatory oculomotor response (contrasting its direction as antipodal to the nystagmus slow phase, or compensatory response), and as past-looking (when the phase-advance of eye-movement occurs in response to an illusory shift in head or body axis and therefore is analogous to past-pointing). Though suggested as early as 1937(10), the phenomenon has not been the subject of concerted interest until the last few years(9, 11-15). Thought to be an expression of the same vestibular drive that produces the saccadic or quick phase of nystagmus, leading eye movement (LEM), teleologically, has been hypothecated as providing a reaction-time delay to be used in recognizing an object of interest, stopping nystagmus, focusing optokinetically on an object, initiating a tracking sequence, stopping head movement(9), or, more fundamentally, as a mechanism to extend the extra-ocular muscles to their optimum lengths for the generation of compensatory (slow-phase) eye movements(16).

LEM becomes disadvantageous when inappropriate vestibular signals that may result from head-turn rates outside the normal range or from the cross-coupling of normal head turns with the turning of a rotating frame of reference (as in the stressful turns of this study) significantly delay the optokinetic fixation of the gaze. These considerations, compounded by the reported observations that LEM may occur in the absence of perceptible nystagmoid eye movements(17), encouraged the design of Experiment 2 of Task II to provide additional data on the eye movements resulting from head turns producing gyroscopic cross-coupling. The experimental objective posed was to determine the absence or presence of LEM following the respective head turns. It was concluded that this objective would be realized if the performance testing of Task II, Experiment 1 was repeated with simultaneous recording of the absolute eye positions throughout the required test trials.

Due to practical necessities, the electro-oculograph used to record eye movements incorporated a-c amplification, producing eye position records of only a relative nature. Of the various validated techniques for recording absolute eye position, it was concluded that the corneal-reflection method offered the most potential for system accuracy, subject freedom, and sequential data collection.

3.2.1 Method. The corneal-reflection technique for measuring eye movement involves the principle that the cornea acts as a convex mirror, reflecting a virtual image of any external source of light directed toward it. The position of this image (the first Purkinje image) is a linear function of the position of the corneal center. As the corneal center moves concentric with the eye, the position of the virtual image shifts in a one-to-one fashion, the locus of its positions conforming exactly to the sequential positions of the optical axis measured in degrees of visual angle. By combining (with appropriate calibration) the locus of the corneal reflections with the field scanned by the eye, the absolute movement of the gaze on that external field will be determined. Combination of the corneal reflection (called the eye spot) with the external viewed field (called the field of regard) may be conveniently done electronically on video tape, or filmed by conventional cinematographic techniques.

In this experiment, a Westgate Laboratories EMC-2F eye-motion camera was used. This instrument reflects the eye spot through a periscope onto the back of the film; the spot's intensity penetrates through to the emulsion at the same time that the conventional lens system photographs the field of regard. Figure 3-6 shows the test subject in the head-turn chair, with the eye camera integrated into the head restraint. A 100-foot roll of 16mm film is loaded into the canister on the left side of the subject's head, with the film guide carrying the film through the camera to the take-up reel on the right side of the subject's head. Eastman 4-X Type 7224 film was used to provide high sensitivity to the eye spot. Photographs were made at 16 frames/second, with lens openings from f11 to f16 and normal ambient illumination.

Eye-camera adaptation and the eye photography technique used for this study are discussed in detail in Appendix C of this report.

3.2.2 Results. Examples of the composite loci of eye movements for all eight subjects for the second trial in each of the six perrotatory orientations are presented in Appendix C, Figures C-9A through C-9C. The loci for testing with the MRSSS static are not included, since they are essentially indistinguishable from the 0°-orientation perrotatory records. The second trial was selected as an illustrative example, since by that trial the major alteration of head-turn rate in response to orientation stress has occurred; using an early trial also ensured inclusion of subjects that aborted testing in subsequent trials.

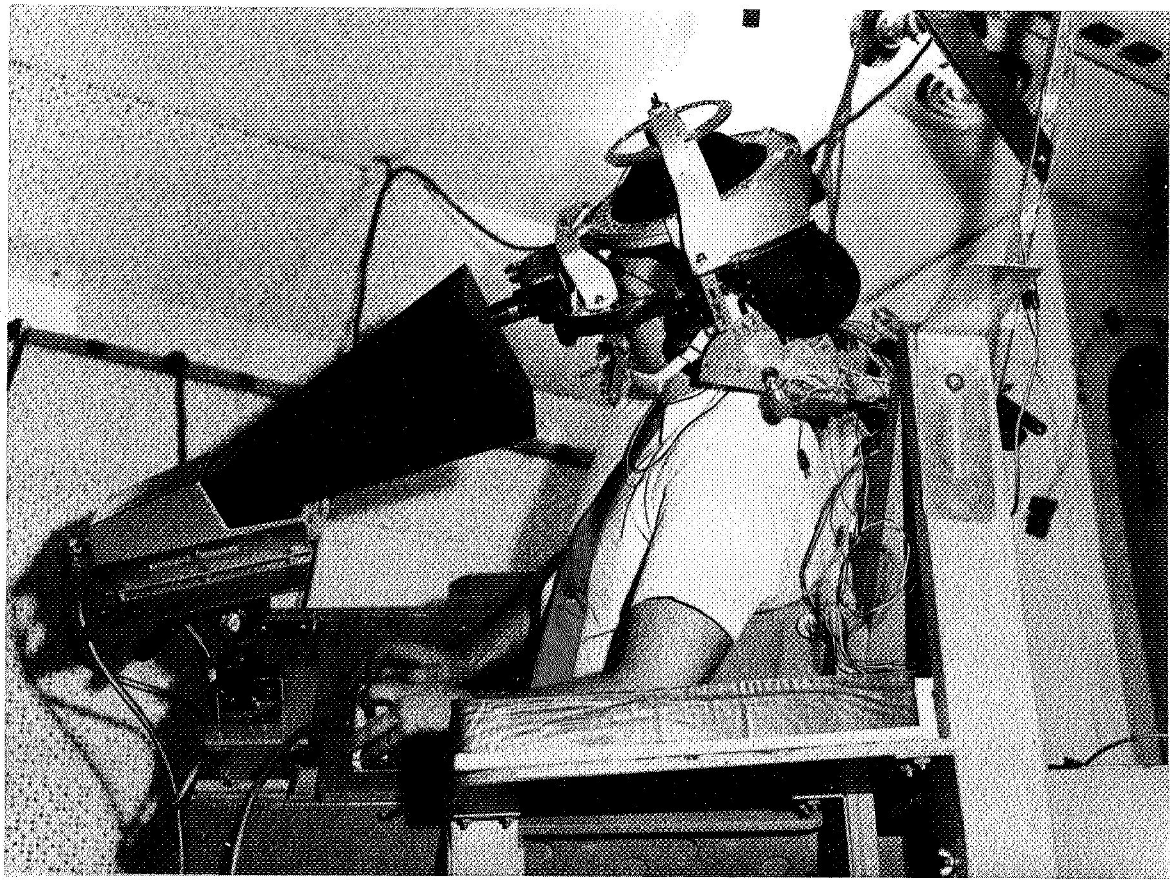


Figure 3-6. Subject Positioned in Chair with Eye Camera Attached to Head Restraint

The frame at which the area of regard is stable means the head turn toward the RATER task is completed.

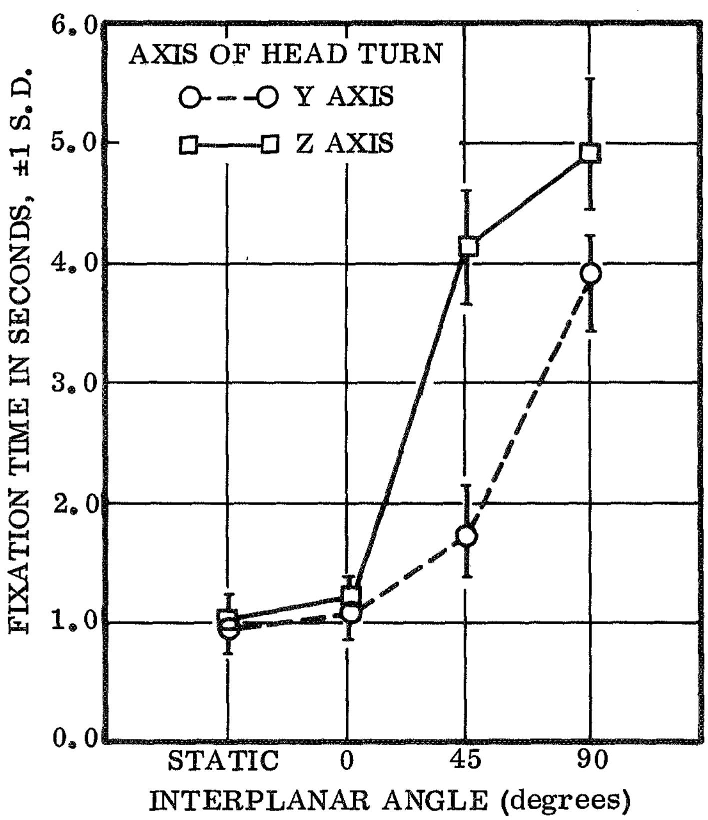
For the convenience of illustrative presentation the turn planes for the Y-axis examples in Figures C-9A and C-9B are shown parallel with those of the Z-axis examples in Figures C-9B and C-9C. However, it should be remembered that the test format required a downward Y-axis head turn from cue light to task and a Z-axis head turn to the right from cue light to task.

It is seen that LEM occurs in all orientations, its amplitude and time duration correlating directly with the extent of performance degradation as related to turn orientation. What is LEM, in the unstressed situations, becomes progressively past-looking as the stress of the turn is increased. Though little evidence of nystagmus is indicated, the loci of stressed eye movements follow the approximate pattern of what nystagmus can be seen in the electro-oculographic traces. Z_{90} describes a flat oval with the predominant drive down and to the subject's left, Y_{90} describes a vertical ellipse. Since the least capability exists for optokinetic control of rolling ocular movements, it is seen that Z_{45} turns (which add a pitch component to the rolling) and Y_{45} turns (which add a yaw component to the rolling) both demonstrate the published observation that, in such two-component situations, the direction of eye movement tends to shift toward that axis having the greatest capability for optokinetic control.[24]

Figure 3-7 is a graphic presentation of eye-fixation time (time duration from the beginning of the subject's head turn to the fixation of gaze within a 1° visual angle in the field of regard) as a function of the various planes of head turn. The 1° visual angle is predicated on the minimum display required for optimal chromatic acuity.

This plot includes fixation times for all trials for all subjects; its direct correlation with the comparable functional expressions of performance degradations in Task I and in Task II, Experiment 1, emphasize the close dependence of perceptual-motor performance on rigid stabilization of the retinal image — even when display shape is not a contingency and discrimination involves essentially primary hues.

The results of this experiment demonstrate an apparent relative increase of the LEM or anti-compensatory response of the oculomotor system as orientations of increased head-turn stress (increased gyroscopic cross-coupling) are encountered by the subject. Whether this apparent increase is due to an absolute increase in the LEM drive or to a reduction in compensatory control is equivocal, but it is apparent that the resulting delay in visual fixation correlates directly with performance degradation and increased vegetative discomfort.



*TIME MEASURED FROM BEGINNING OF SUBJECT'S HEAD TURN TO FIXATION OF EYE MOVEMENT WITHIN ±0.5° OF VISUAL ANGLE.

VALUES ARE MEAN TIMES FOR ALL TRIALS FOR ALL SUBJECTS.

Figure 3-7. Eye-Fixation Time* as a Function of Head-Turn Plane

3.2.3 Requirements for Additional Study. The increased difficulty in visual fixation upon the target, following head turns out of the plane of vehicle spin, appears responsible for performance degradation. This can be avoided by confining movement of the head to the plane of spin. In the operational space station the Y axis is the only practical axis to use at zero degrees interplanar angle, and it appears that this axis can be extended to a 45° interplanar angle from that of vehicle spin. A display task, however, will usually impose a control response, and it was now necessary to show that this orientation was also satisfactory for hand-arm motions associated with the display orientation, since the Coriolis deflection of a limb passively moved in an environment with a high angular velocity is quite noticeable.

3.3 EXPERIMENT 3: CONTROL ARRANGEMENT. The previous experiments have demonstrated that Y-axis (nodding) head motions out of the plane of spin result in less disorientation than comparable Z-axis (yawing) head motions. This would indicate that displays would be best oriented on the leading or trailing bulkhead and arranged in a vertical presentation. Control problems in such an arrangement, however, could possibly negate the advantages. Reach along the vertical axis would be in the plane of vehicle spin, but would be a linear translation in a radial direction and consequently subject to maximum Coriolis acceleration. Horizontal control arrangement would require reach motions parallel to the axis of vehicle rotation and consequently would have a minimum Coriolis deflection. To assess the magnitude of this possible complication, the same Task II performance test (RATER) was used, but with the response buttons movable so that the volume of the reach envelope could be varied. Horizontal arrangements were compared to vertical arrangements. To eliminate artifacts due to vestibular stimuli, the subjects had their heads restrained in a fixed position.

3.3.1 Method. The test subjects occupied the chair shown in Figures 3-8 and 3-9. They were positioned so their long (Z) body axis was in the spin plane, facing the direction of rotation. This attitude approximates the "in-work" head-torso-equipment relationship to be encountered in a rotating spacecraft. A 36-inch long and 3-inch wide test control panel faced the subject, far enough from him to allow testing of the largest mechanically possible reach envelope. This panel, swivel-mounted on plywood backing, allowed for repositioning of its four response buttons along its length. For this test, three envelopes were used, with the two lateral buttons being 12, 24, or 36 inches apart and

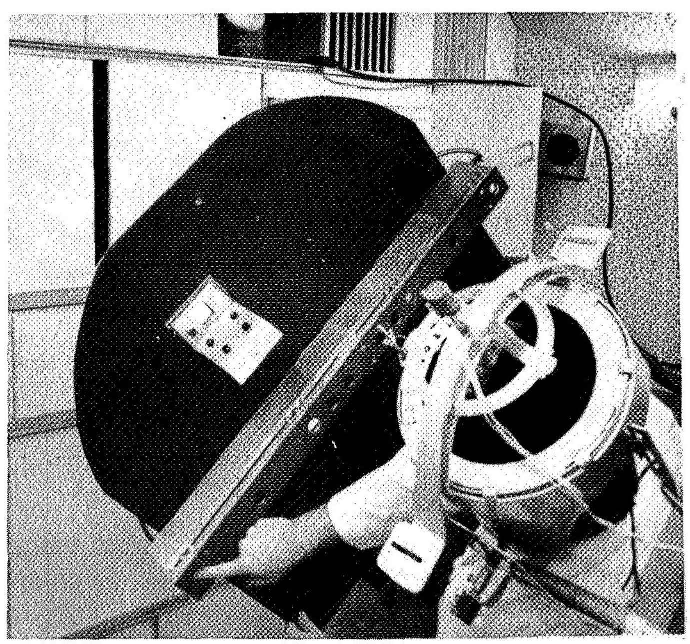


Figure 3-8. Horizontal Digital Control Task Set for 36-Inch Envelope

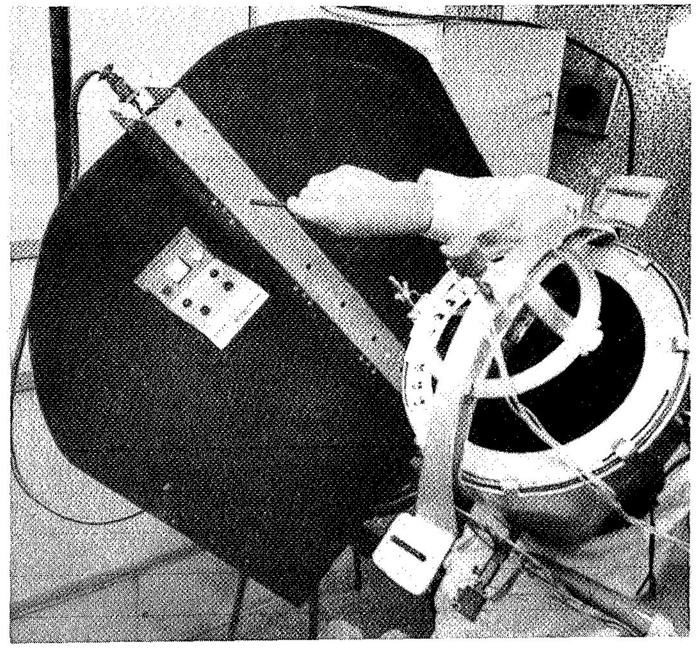


Figure 3-9. Vertical Stylar Control Task Set for 24-Inch Envelope

medial-button range trisections being 4, 8, or 12 inches respectively. The entire panel swiveled to allow alignment with the subject's vertical (Z) or horizontal (Y) axis. The buttons were continuously illuminated to contrast with the panel surface.

The test sample consisted of four active naval pilots from N.A.S. North Island, San Diego. They were Caucasoid males, 23 to 30 years years of age and 6 feet, 2 inches to 6 feet, 4-1/2 inches in height. All subjects were trained to an asymptotic plateau prior to actual testing in the static, and then dynamic, simulator.

The RATER task, as in the previous study, required that the subject press the correct button in response to each color displayed in random sequence. The self-paced RATER mode was again used, with the next display appearing only when a correct response was made. Each test sequence was made up of five 15-second trials spaced by 5-second rest periods. Each subject performed a sequence for each of the three envelopes, for both vertical and horizontal alignments, with the simulator static and dynamic. A single test comprised 12 sequences.

Because initial (pilot) runs suggested that perhaps the reach problems would be less than anticipated, a duplicate test was run but with an altered format to increase test sensitivity to stress.

The initial format required digital percussion of one-inch diameter buttons (an operational level of difficulty). The added format required percussion of 3/8-inch diameter buttons with a 1/4-inch diameter stylus. This second format expanded the total number of trial sequences for each subject to 24. The balance of major permutations and sensitivity formats used to null out cumulative effects is shown in Table 3-1. In the table the letters H and V refer to the horizontal or vertical body axis of the subject to which the test control panel is parallel. Subscripts denote distance, in inches, separating the two lateral buttons. The permutations apply to both static and dynamic situations in that order.

Table 3-1. Experimental Format

SUBJECT	ORDER OF TECHNIQUE	PERMUTATIONS					
A	1) Stylus 2) Finger	V_{12}	H_{12}	H_{24}	V_{24}	V_{36}	H_{36}
B	1) Stylus 2) Finger	H_{36}	V_{36}	V_{12}	H_{12}	H_{24}	V_{24}
C	1) Finger 2) Stylus	H_{12}	V_{12}	V_{24}	H_{24}	H_{36}	V_{36}
D	1) Finger 2) Stylus	V_{36}	H_{36}	H_{24}	V_{24}	V_{12}	H_{12}

3.3.2 Results. The total score was number correct minus errors. Table 3-2 summarizes individual performance. In the table, figures to the left of the slash represent total correct responses minus wrong responses recorded during the five 15-second trials of the static sequence indicated; figures to the right of the slash represent dynamic data collected during rotation at 12.2 rpm.

Table 3-2. Individual Performances Static and Dynamic Data

TECH-NIQUE	DISTANCE SEPA-RATING LATERAL BUTTONS	SUBJECT							
		A		B		C		D	
		HORIZ.	VERT.	HORIZ.	VERT.	HORIZ.	VERT.	HORIZ.	VERT.
Finger	12"	92/100	92/94	89/91	84/90	97/97	98/90	90/94	93/100
	24"	88/91	85/82	85/86	80/79	85/78	81/84	89/83	84/88
	36"	86/87	77/81	79/77	71/75	77/77	77/78	76/75	84/79
Stylus	12"	87/88	84/83	68/78	82/75	76/75	72/76	86/85	79/77
	24"	71/73	75/66	66/61	71/69	58/56	63/67	70/63	67/65
	36"	61/69	67/57	56/57	66/72	66/51	56/60	75/58	69/63

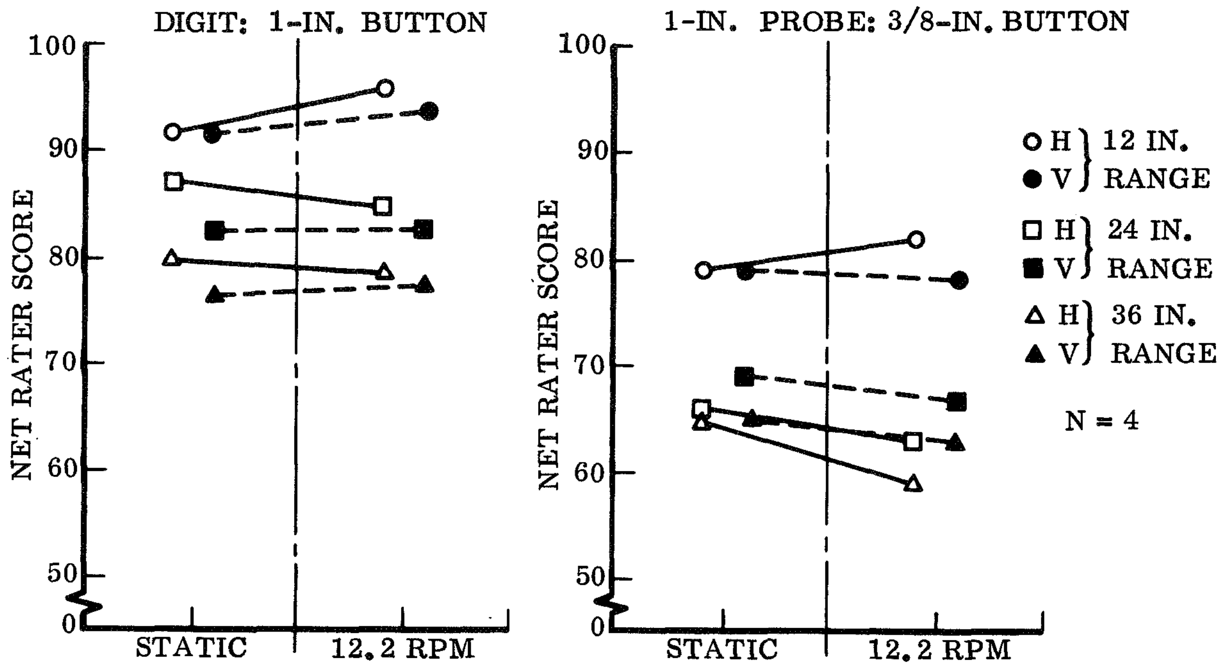


Figure 3-10. Horizontal vs. Vertical Reach Effectiveness During Rotation

Reach effectiveness as a function of horizontal or vertical alignment and for a static or spinning environment are plotted in Figure 3-10. Table 3-3 contains the results of a statistical evaluation of the same functional relationships.

Table 3-3. Results: Signed-Rank Test

DIFFERENCE IN REACH EFFECTIVENESS*: ORIENTATION VS. ORIENTATION		
ORIENTATION COMPARISON	FINGER**	STYLUS***
Horizontal_S vs. Horizontal_D	$P > 0.20$	$P > 0.20$
Horizontal_D vs. Vertical_D	$P > 0.20$	$P > 0.20$
Vertical_D vs. Horizontal_S	$P > 0.20$	$P > 0.20$
Vertical_S vs. Vertical_D	$P > 0.20$	$P > 0.10$
Vertical_D vs. Horizontal_S	$P > 0.20$	$P > 0.20$
Horizontal_S vs. Vertical_S	$P > 0.20$	$P > 0.20$

S = MRSSS Static D = MRSSS Dynamic (12.2 rpm)
*Effectiveness Index = mean RATER score for 12 scores (4 subjects x 3 reach envelopes).
**1-inch button diameter.
***1/4-inch stylus diameter and 3/8-inch button diameter.

Since the matter of individual judgment (information analysis and correct choice of several possible responses) was not in question as far as this experiment was concerned, few errors would be expected. Inaccuracies, if any, would be reflected in fewer total correct responses during the test period; such was the case. The vertical trials should have been affected maximally by Coriolis deflection, particularly at the 36-inch dimension, and the horizontal trials minimally or not at all.

The difference in total correct responses expected or achieved between the vertical and horizontal presentations was not significant, as seen in Tables 3-1 and 3-2; there is no consistent difference between static and dynamic results. Even the use of a stylus and reduced target area, to exaggerate the influence of Coriolis and more clearly establish its relationship with reach, failed to exhibit decrement as to alignment axis or force field. The only score reductions were due to the added mechanical constraints of a larger envelope or a smaller diameter button.

Coriolis force has no measurable effect on the precision and accuracy of reach activities in the rotating environment under the test conditions of this study. Although the influence of Coriolis acceleration on reach may become significant at higher angular velocities, the requirement for such velocities is very unlikely.

SECTION 4
DISCUSSION

The experiments of Tasks I and II, measuring perceptual-motor performance following 70° head turns, in a simulator spinning at 12.2 rpm, indicate that, within the constraints of these experiments, pitching (Y-axis) head turns are significantly more tolerable than yawing (Z-axis) head turns when turns are out of or into the plane of simulator spin. These experiments were designed such that identical yaw and pitch head turns would produce theoretically identical rolling vestibular responses when cross-coupling with the environmental spin.

Cross-coupled accelerations were calculated for these experimental head turns made at an angle relative to the spin plane. The results of these calculations are presented in Table 4-1. Head yaws from right to left, pitches from down to up, and rolls from left to right were taken as positive.

Table 4-1. Cross-Coupling Effects*

HEAD TURN	CROSS-COUPLED ACCELERATION α_{G_ϕ}	α_{G_ψ}	α_{G_θ}
Z_{90}	$-\omega_v \omega_{h_\psi}$	None	None
Y_{90}	$-\omega_v \omega_{h_\theta}$	None	None
Z_{45}	$-0.5\ \omega_v \omega_{h_\psi}$	None	$-0.707\ \omega_v \omega_{h_\psi}$
Y_{45}	$0.5\ \omega_v \omega_{h_\theta}$	$-0.707\ \omega_v \omega_{h_\theta}$	None

*Dynamics of the study environment were described by Mr. J. C. Ballinger.

Symbols α_{G_ϕ}, α_{G_ψ}, and α_{G_θ} refer to cross-coupled angular accelerations about the roll, yaw and pitch axes respectively; ω_{h_ψ} and ω_{h_θ} are the actual angular head velocities of yawing and pitching made by the subjects; and ω_v is the angular velocity of the centrifuge.

It is seen that cross-coupled accelerations about the roll axis result from each of the four head turns; the two 90° orientations have cross-coupled accelerations about the roll axis exclusively. Since the cross-coupled acceleration resulting is directly proportional to the specific head turn velocity, it is apparent from the experimental head-turn rates that, for the 90° orientations, the tolerable cross-coupled acceleration due to a head pitch is about 1.4 times that for a yaw (see Figure 2-2). This difference is of interest, since the cross-coupling is about the same axis (roll) in both cases.

For the 45° orientations, a yawing or pitching motion produced a corresponding cross-coupled acceleration in pitch or yaw, respectively, in addition to an identical roll response in both cases. From Figure 2-2 it would appear that a greater tolerance exists for pitching than for yawing in the 45° orientations as well.

Having established that Z-axis turns at an angle relative to the spin plane are more intolerable as to performance and comfort when compared to comparable Y-axis turns (even though they produce theoretically equal vestibular roll cross-couples), it is desirable to postulate a basis for the increased Z-axis stress. An attractive hypothesis involves the common factor pervading all sensorimotor disorientation, including autonomic sequelae and motion sickness: conflict of sensory cues.

Consider the yawing (Z-axis) head turn. Under conventional environmental circumstances, a rapid head turn to a person's right or left is not a purely Z-axis turn, but includes a pitching component toward the proximal shoulder. In a large amount of day-to-day cranial yawing the relative head-to-torso turn and/or turn rate is reduced by the ease of torsional movements of the long body axis; to move visual fixation to a new image in the yaw plane tends to involve less eye-to-skull rotation due to the same torsional ease. In addition, oculomotor balance in the yaw plane involves a slowly decaying vestibular signal (time constant of 15 sec) and a strong optokinetic reflex.[18]

When these same Z-axis turns are made normal to the spin plane of a rotating system, the cross-coupling produces a strong vestibular response in a plane orthogonal to the coupled rotations (in this study producing a vestibular signal in the roll plane). The rolling anti-compensatory response is strong but of relatively shortened time constant, and is antagonized by an optokinetic control of relatively reduced capability.[18] An additional conflict results from an optokinetic response still occurring in the yaw plane but within an oculomotor context of no yaw vestibular signal.

This major and unpredictable oculomotor disorganization could logically produce the observed uncontrolled LEM, oscillatory eye movements and concomitant performance decrement. Within the test constraints, the prevention of Z-axis torso rotation and cranial pitching toward the shoulder during the Z-axis head turn could add to the distortion in total stimulus.

When the Y-axis head turn is considered, there appears to be a reduced opportunity for oculomotor disorganization. Under conventional environmental circumstances, Y-axis head and eye motions are pure and unmodified by torso movements. Vestibular responses decay more rapidly (time constant = 5 sec) than in the yaw plane and the optokinetic control is weaker.[18] When the same Y-axis head movement is made normal to the plane of environmental spin, the cross-coupled response occurs in a plane orthogonal to the interacting rotations (in this test the response occurring in the roll plane). Though the resulting vestibular gyroscopic response is disorienting, it has a decay rate, and is opposed by an optokinetic reflex, of comparable magnitude to that occurring in the pitch plane.

In addition, it might be surmised that the greater predominance of Z-axis head motions in normal existence may entail a more difficult deconditioning process when a naive subject is placed in a rotating environment.

The problem of tangential Coriolis accelerations reducing radial reach effectiveness in an environment rotating at 12.2 rpm was anticipated to be a serious one prior to running Experiment 3 of Task II. To the surprise of the investigators, no decrement in reach effectiveness occurred, even when the requirements of the stylus percussion produced a task difficulty exceeding that of any anticipated operational control problem.

The ability of subjects to rapidly adjust their performance to environmental rotation has been previously noted. This rapidity of adjustment is in contrast to the slower visceral adjustment that apparently is dependent upon complete suppression of signals that cause conflict in the stressful orientations.[19]

In prior studies, tests such as tracking[20] and ballistic aiming[21] have been used to require stressful head turns, and even when experiencing overt symptoms of motion sickness many subjects have performed precision perceptual-motor tests without significant decrement.[22] Such results substantiate those of the present study.

Studies of prolonged rotation have indicated that within 48 hours of rotation at 6 rpm, complete adjustment to the environment occurs.[21] This adjustment appears to be a stimulus-bound central suppression of labyrinthine signals, as post-adjustment caloric stimulation of the labyrinths elicits a full response.[21] This suggests that the console orientation constraints discussed need apply only during the initial period of rotation.

These studies demonstrate the limitations of ground-based simulation of rotating space vehicles. It is impossible to duplicate in normogravic rotational simulators the actual profile of cross-coupled stresses that will be experienced in a rotating space vehicle, where the majority of random head movements will be the most stressful, that is, yawing motions normal to the spin plane. This very stressful profile could hasten adaptation of the crewman, but could also exceed his tolerance, producing a possible slowing of adaptation.

In a previous study, all four subjects exposed in the MRSSS for five days at 6 rpm adapted within 48 hours.[21] Yawing head movements were essentially in the plane of spin during this adaptation period, but no difficulties were reported due to yawing head motions when they were lying on the bunks. The bunks are arranged radially, putting the recumbent subjects in the plane of spin. Considerable time was spent in this position since it was the only area available to the two "off duty" subjects. They did their reading and television viewing in this position and if a significant problem existed it probably would have been reported. It is possible that the four-hour periods of sleep in this position may have contributed significantly to their adaptation to Z_{90} turns; however, it is generally felt that more active interaction is required for adaptation This suggests that, if suppression of vestibular signals is the mechanism for adaptation, it is a general phenomena, and that the Y-axis and small-angle Z-axis turns provide adaptation to stimuli not generally received during the process, e.g., Z_{90} cross-coupling.

SECTION 5

REFERENCES

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APPENDIX A

OPERATION AND CONTROL OF THE MRSSS CENTRIFUGE

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OPERATION AND CONTROL OF THE MRSSS CENTRIFUGE

The control and actuation system of the MRSSS centrifuge permits both manual and automatic rotation, declination (inclination) and perturbation (oscillation) of the test chamber. The functions may be carried out on a separate or simultaneous basis. Figure A-1 shows the main centrifuge control console, and Figure A-2 depicts schematically the control and actuation system. The system allows controlled declination of up to 50° and controlled perturbation of up to $\pm 10^\circ$. Rotation and declination were used during this study.

The centrifuge complex receives precision calibration prior to each operation. Parameters including angular velocity, rise time, duration and stabilization are monitored at the control console. For this study the operational profile was as follows: With subject and onboard examiners in their initial test positions within the MRSSS, the centrifuge was accelerated at 2.0 rpm^2 until the desired angular velocity of 12.2 rpm was reached. This acceleration of the centrifuge gave a rise time of slightly more than five minutes, thus producing only subliminal vestibular stimulus as long as the subject's head was kept reasonably immobile. As the angular velocity of the simulator increased, the setpoint potentiometer on the controller was varied to produce the correct declination angle for the inertial resultant. The angular velocity of the centrifuge was controlled within an error range of less than ± 0.01 rpm. Deceleration to stop reversed the profile of the acceleration procedure.

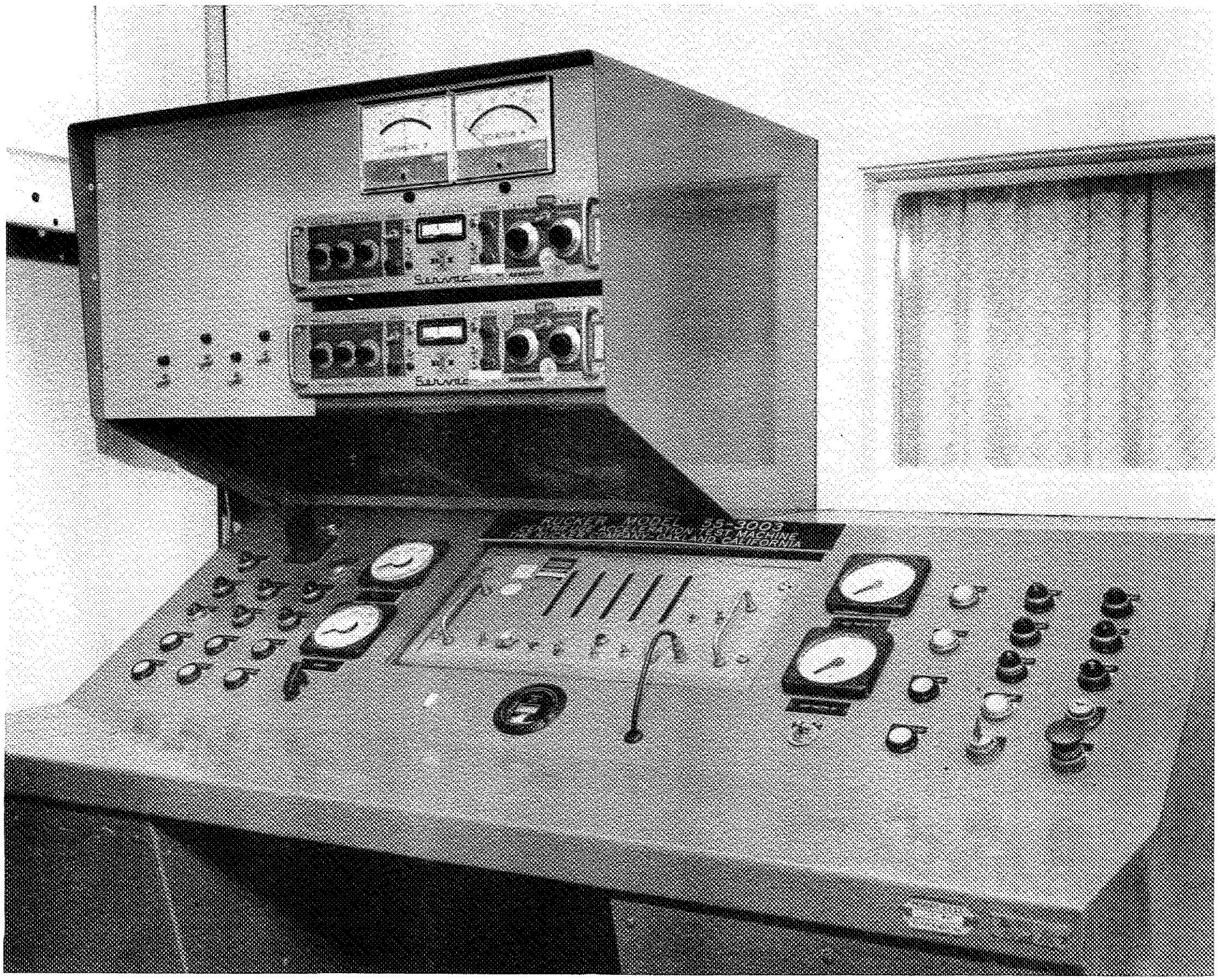


Figure A-1. Main Centrifuge Control Console

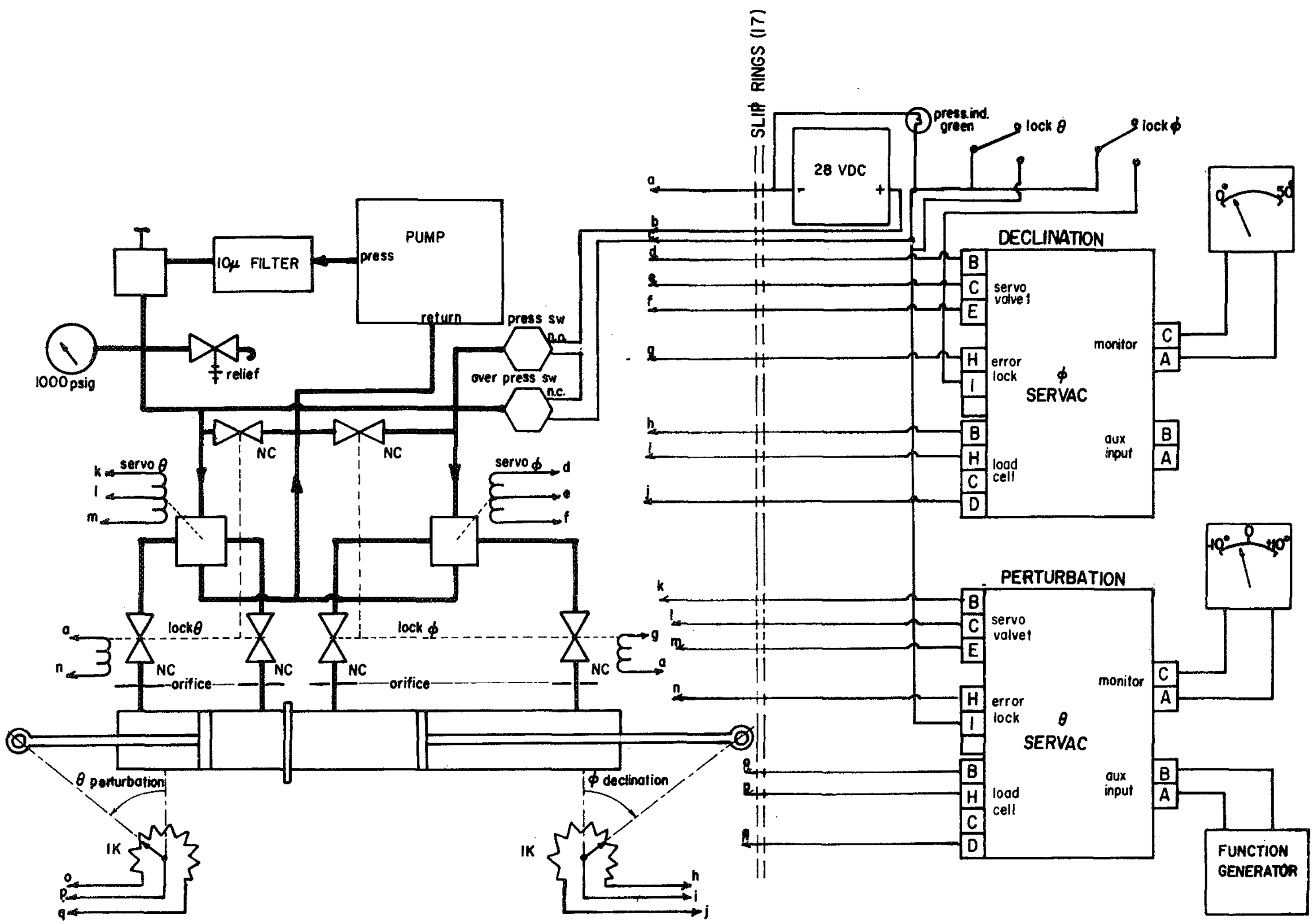


Figure A-2. MRSSS Control and Actuation System Schematic

APPENDIX B

TYPICAL ELECTRO-OCULOGRAMS FROM TASK II, EXPERIMENT 1

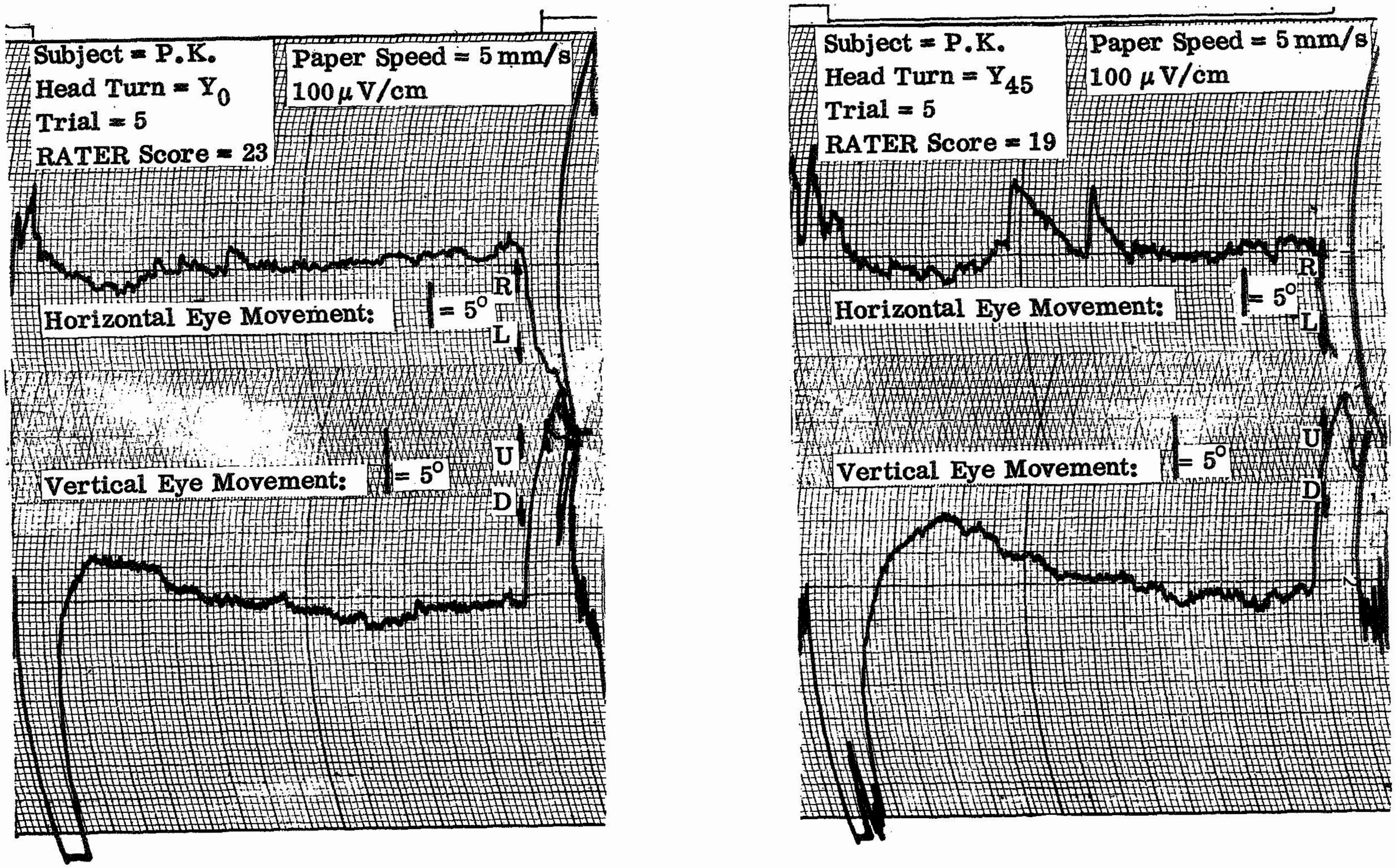


Figure B-1. Subject P.K. During Y_0 and Y_{45} Turns

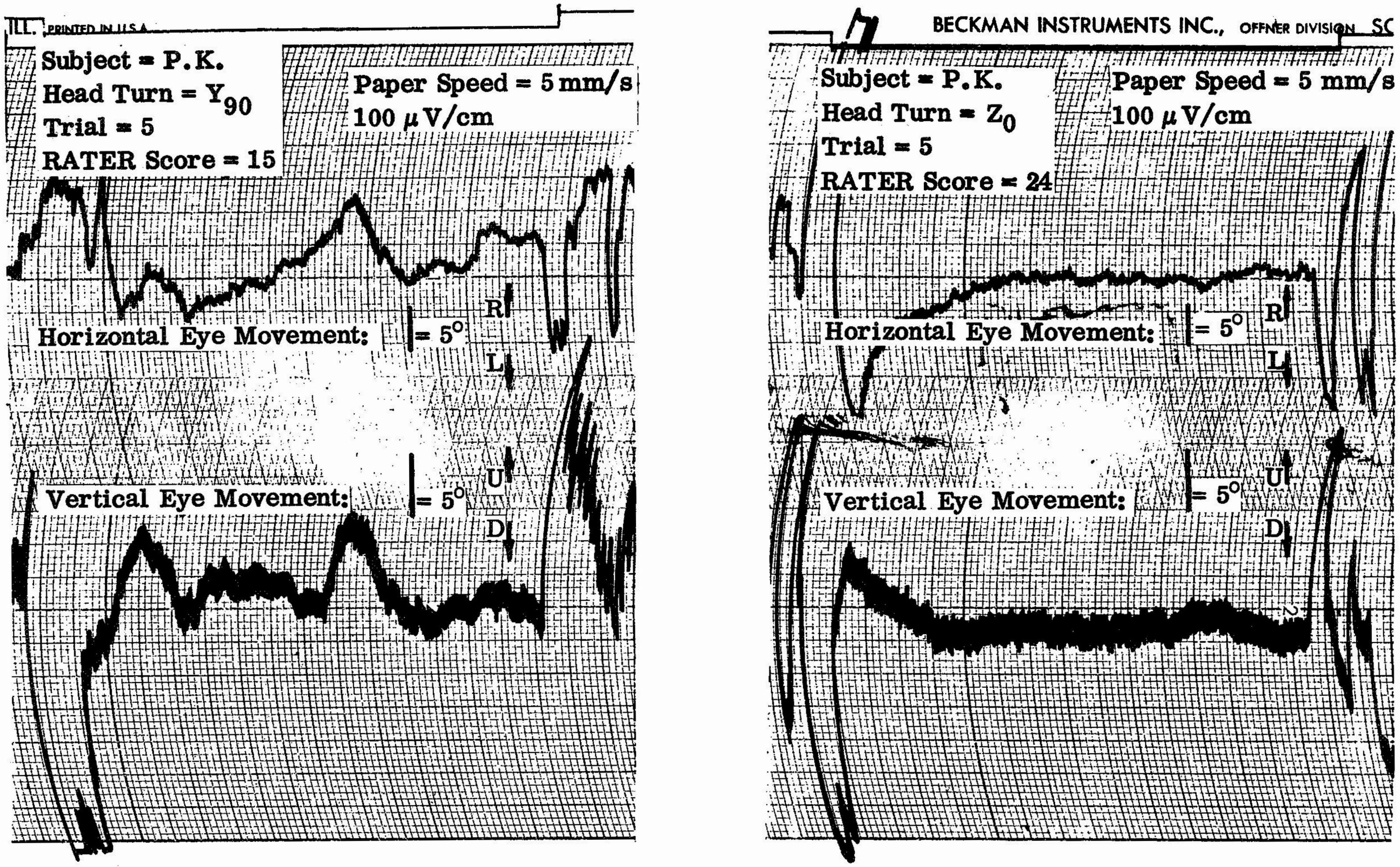


Figure B-2. Subject P.K. During Y_{90} and Z_0 Turns

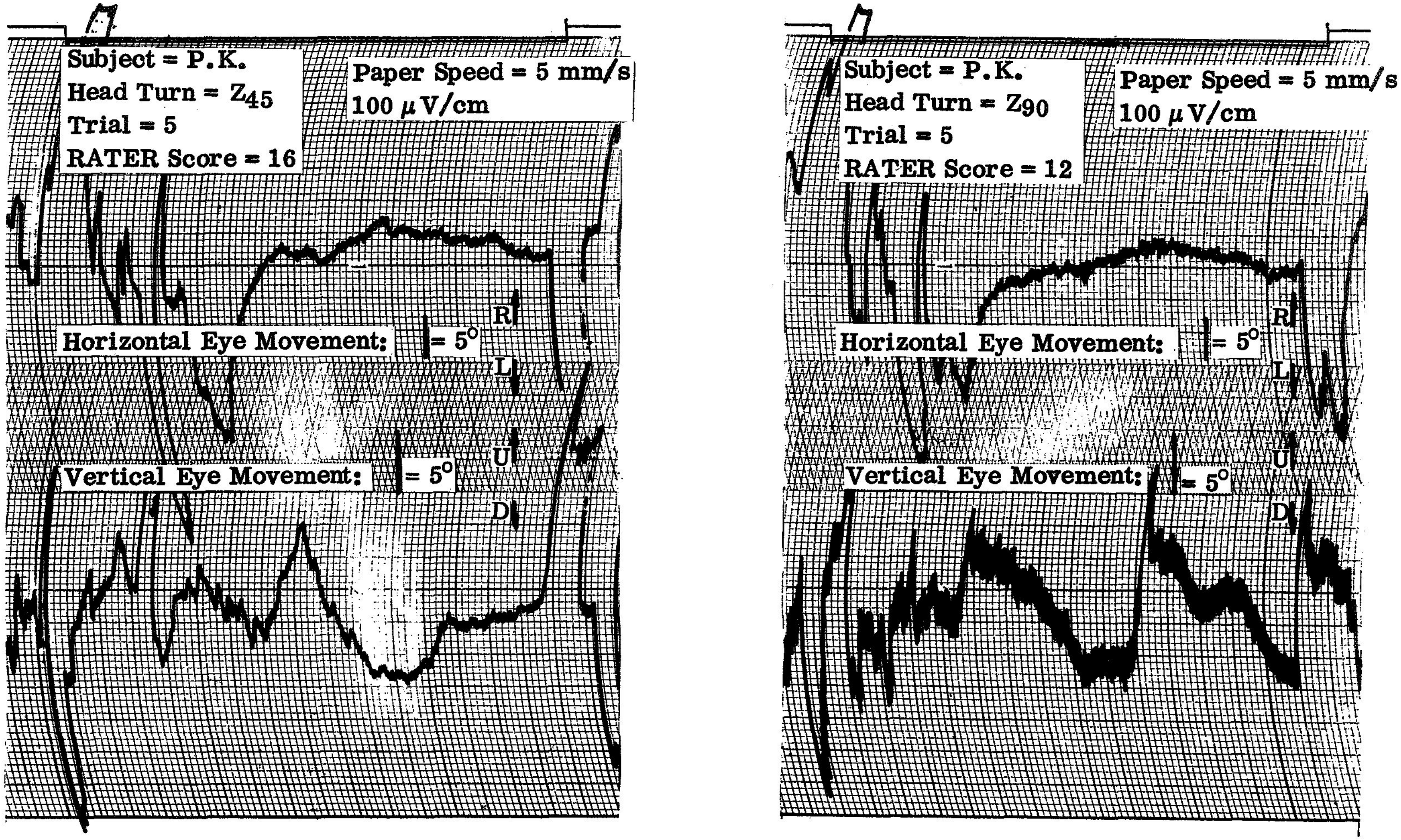
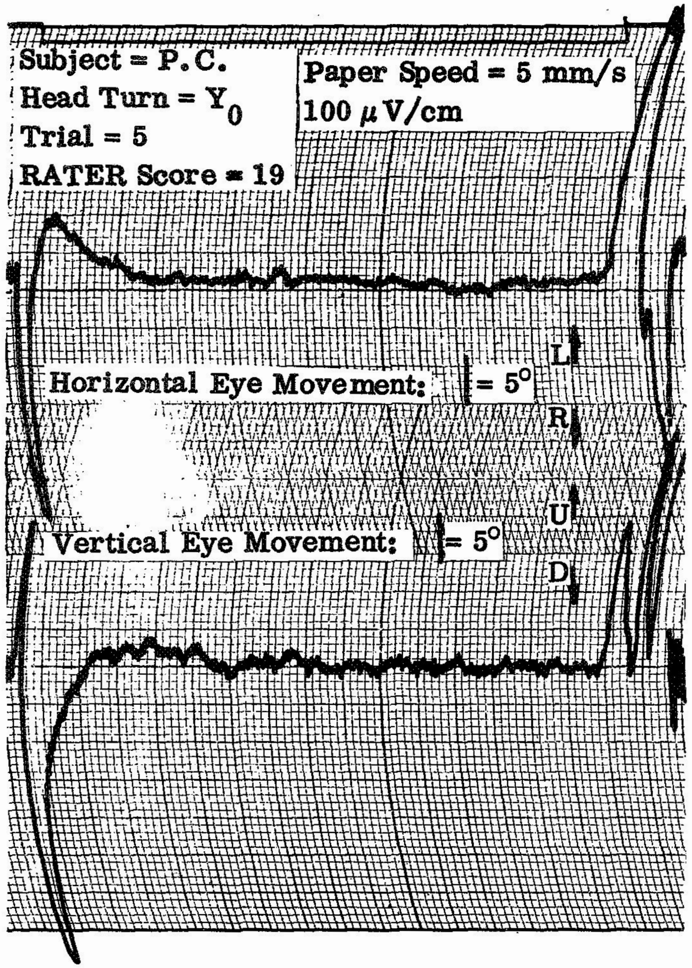


Figure B-3. Subject P.K. During Z_{45} and Z_{90} Turns



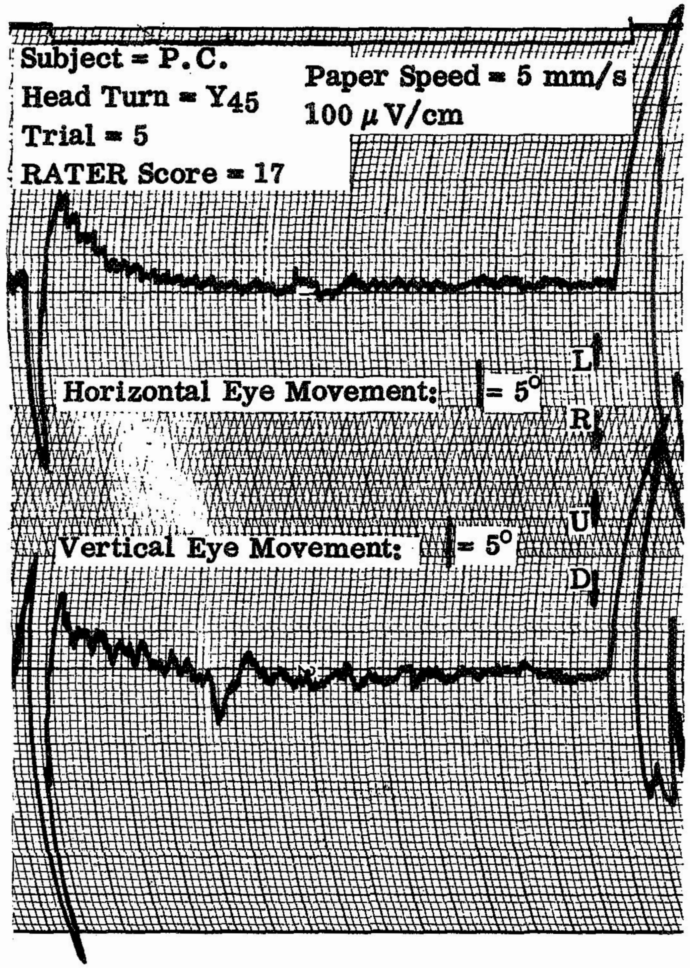


Figure B-4. Subject P.C. During Y_0 and Y_{45} Turns

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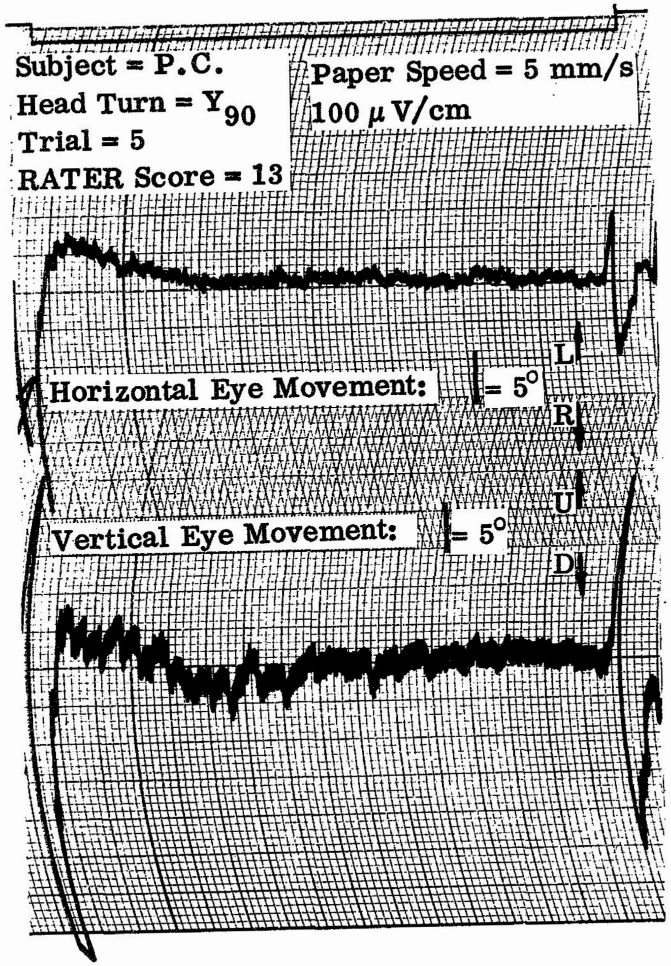

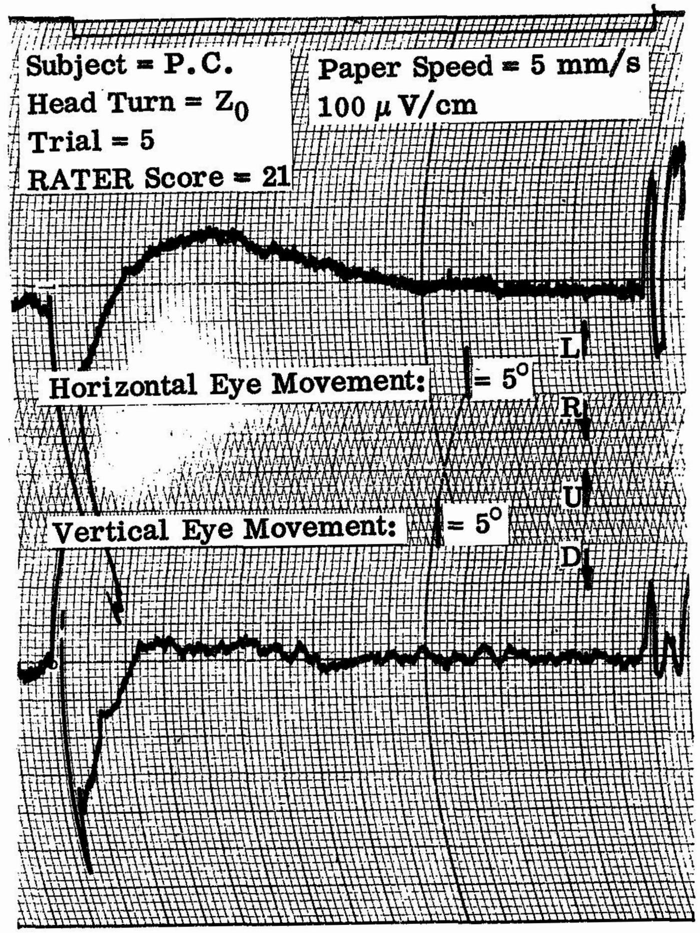

Figure B-5. Subject P.C. During Y_{90} and Z_0 Turns

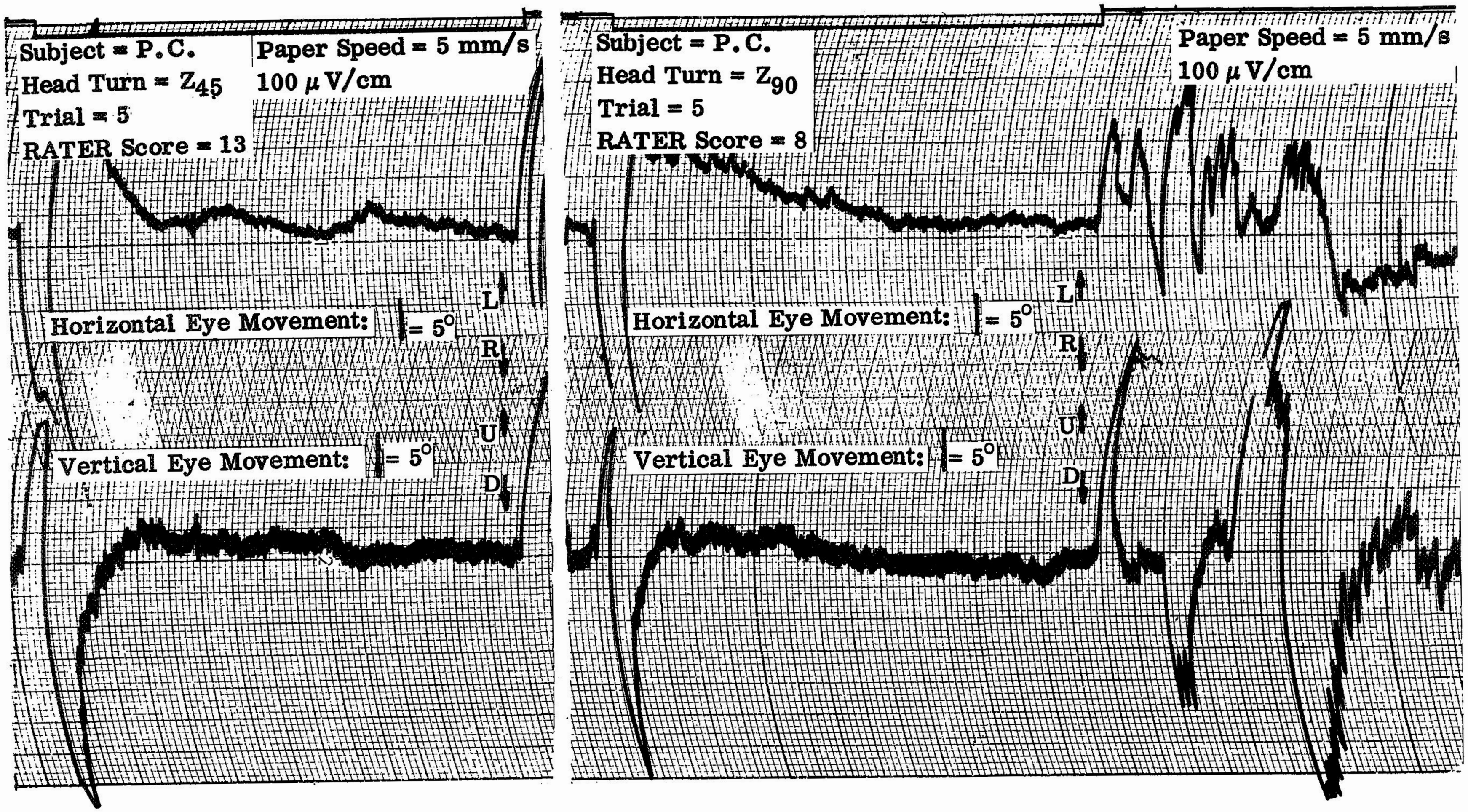

Figure B-6. Subject P.C. During Z_{45} and Z_{90} Turns

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APPENDIX C

EYE PHOTOGRAPHY TECHNIQUE FOR TASK II, EXPERIMENT 2

APPENDIX C

EYE PHOTOGRAPHY TECHNIQUE FOR TASK II, EXPERIMENT 2

Adaptation of the eye camera for use in this study involved meeting two primary test requirements: the prevention of significant (more than $\pm 0.5°$) relative movement between the subject's head and the camera optics, even during the sequences of head turns; and the support of the camera and head-restraint masses so that the subject could move his head with a freedom approaching that when unencumbered.

To prevent cranial movement relative to the camera optics, the inflexible continuity of the maxillary arch was utilized with a bite bar having an exact dental impression for each subject. Some problem was posed because, with the subjects being active naval pilots, prediction of the specific individuals that would be participating could not be done in advance, nor could time be allowed on the test day for following the standard dental impression procedure. Taking a direct permanent plastic impression would involve a lengthy curing period, the discomfort of the exothermic reaction, and the possibility of dental complications that might require emergency professional aid. At this point, J. F. Jones, D.D.S., was contacted. In addition to providing other invaluable aid in the form of instruction and materials, he suggested the use of a combination of Tra-Ten impression trays and Hydro Jel impression material to solve the somewhat unique problem.

The components suggested (shown in Figure C-1) proved entirely satisfactory. Only an upper impression tray was required. This was reduced in depth and shortened to preclude any subsequent stimulus to the soft palate during use, and was epoxied to a stainless steel frame bar for securing to the head restraint for testing.

The impression colloid is formed by homogenizing powder and tap water using a spatula and rubber bowl. The homogenate is then smeared on both surfaces of the tray and an impression taken of the subject's bite for two minutes. This procedure produced accurate upper (Figure C-2) and lower (Figure C-3) dental impressions. For all subjects, the impressions withstood almost continuous use for three to four hours without breaking down, yet could be peeled instantly from the tray to allow reuse of the bite bar. And, of primary importance, the bite bars prevented significant cranial movement relative to the camera.

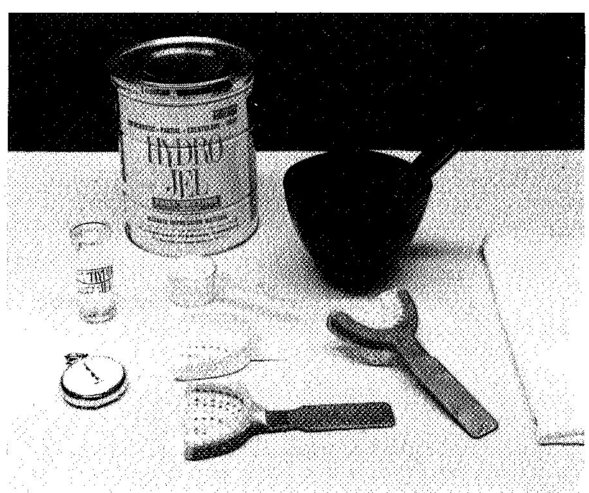

Figure C-1. Bite Bar and Dental Impression Material

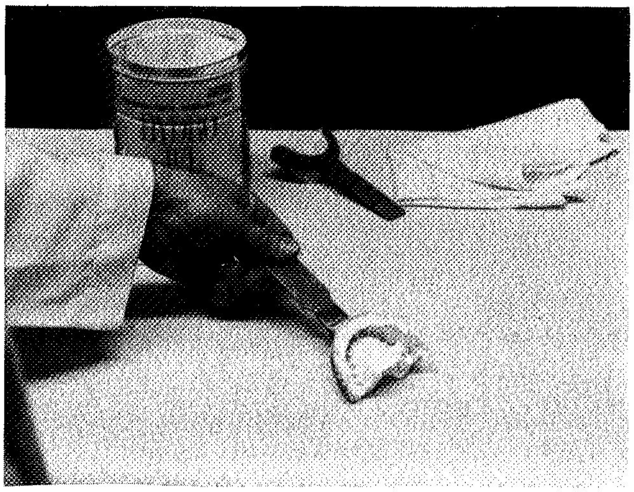

Figure C-2. An Upper Dental Impression

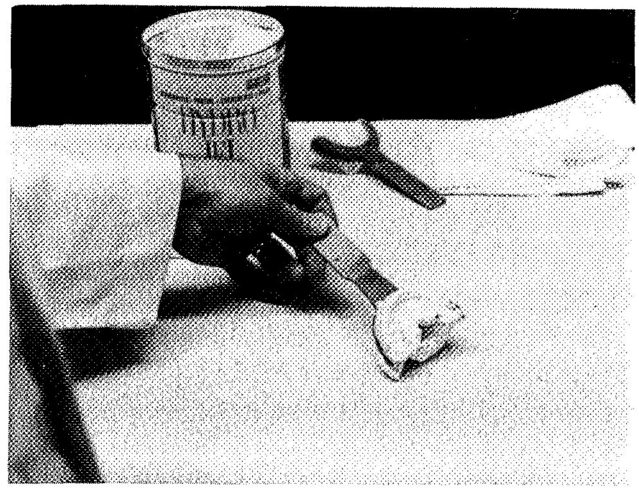

Figure C-3. A Lower Dental Impression

Two pairs of springs were used to support the mass of the head restraint and camera: one pair for Z-axis turns and one pair for Y-axis turns, each pair involving antagonists producing the balance required for smooth support of head turn. By precise vectoring of the spring tensions, the 10-pound mass of the camera complex was completely compensated. Figure 3-6, which shows the subject wearing the eye camera complex, was photographed prior to installation of the springs.

The subjects were volunteers, all active pilots at N.A.S., North Island, San Diego. They were Caucasoid males of 29 ±4.6 years of age, and 5'10 ± 3.4" in stature. One subject was tested each day and eight subjects were able to finish at least one or more trials in each of the eight different sequences.

The same basic test format was used as in Experiment 1 of Task II. The subject was asked to perform a 10-trial RATER performance sequence in each of the eight combinations of turn orientation and force field environment: Y-axis head turn with the MRSSS static, Y-axis head turns with the turn plane at 0°, 45°, and 90° to the plane of the MRSSS rotating at 12.2 RPM, and Z-axis head turns in the same four situations. In view of the added vegetative stress of the bite bar and since the object of the experiment was limited to determining the presence or absence of "past-looking", balanced permutations of the orientation sequences for the subjects were not used (as in Experiment 1 of Task II). The order felt to be the least traumatic was used for all subjects. Each sequence consisted of ten 15-second trials spaced by 20-second rest periods.

Upon arrival at the MRSSS laboratory, the subject's dental impression was taken while he was being fitted with EOG and EKG electrodes. He was then trained on the RATER until his performance reached an asymptotic plateau.

The subject's EOG leads were then attached to a Beckman Type RS Dynograph and the EOG calibrated. EOGs were recorded using a 9806A a-c coupler with a 1.0 second time constant, a 461B pre-amp set at 1.0 millivolt/cm sensitivity, and a 462 amplifier at 0.1 millivolt/cm sensitivity. For calibration, the subject was positioned at an American Optical Model 12230 perimeter and asked to execute a series of repetitive 5° and 10° visual excursions, in rhythm with a one/second metronome beat, with the recorder at its slowest paper speed.

Next, the subject was placed in the test chair as shown in Figure 3-6, the head restraint adjusted for comfort of both Y- and Z-axis head turns, and the bite bar placed in his mouth. The bite bar was rigidly bolted to the eye camera after it was determined that the camera complex was positioned so the corneal light source was reflected by the left eye of the subject and the reflected eye spot was satisfactorily focused and centered by the periscope onto the transparent frame of the calibration leader. Final centering and focusing of eye spot was done with the subject's gaze fixed directly on the collimated display of the RATER.

The eye camera's center was in the sagittal plane passing through the subject's left eye, but offset from the mid-sagittal plane of the subject. The off-the-shelf camera is designed so the optical axis of the camera and mid-sagittal plane of the subject converge at a point five feet in front of the camera. Since this convergence distance could not be easily shortened and it was desired that the subject's eye-to-display distance be kept in an operational range (one to two feet), the proximal surface of the RATER's collimator was laminated with a plastic square 18 inches on a side, divided into 1-inch squares. This calibration grid was not attached when the photograph for Figure 3-6 was taken, but the configuration can be seen in Figure C-4, with the spherical distortion imposed by the lens. The letters and numbers on the grid were included to individuate squares should a reduced camera-to-grid distance render designation of eye spot location on field of regard difficult. This problem, however, never materialized. Figure C-4 is a series of positive prints from the 16-mm film; in each frame the white spot is the eye spot and the black oval in the lower right is the orifice of the RATER display. Were the grid at five feet in front of the focal plane of the camera, with the subject fixed on the RATER display, the white spot would be superimposed on the black spot. But with convergence interrupted, calibration of the eye-motion camera proceeded as follows. Fixation points were inscribed on the grid surface at 1-inch intervals, vertically above and below, and horizontally to the left and right of the RATER display orifice (A, B, and C above, D, E, and F below, etc.). Displaced from the area where the subject would be fixing his gaze, but near the center of the field of regard (due to the camera offset), the same letters were duplicated in two short, parallel arrays (indicated by the pencil in Figure C-4). The strips read O-A-O-B-O-C-etc., the O symbolizing the RATER display orifice. A complete calibration sequence consisted of the on-board examiner audibly reciting the above order of letters to the one/second beat of the metronome while simultaneously designating each letter with a pencil and while the subject was visually fixing each letter. Both cinematographic (16 f/s) and electro-oculographic data were continuously recorded. Figure C-4 is composed of five frames from a representative eye motion camera calibration film (subject R.A.'s Z-axis calibration film), photographed with normal ambient

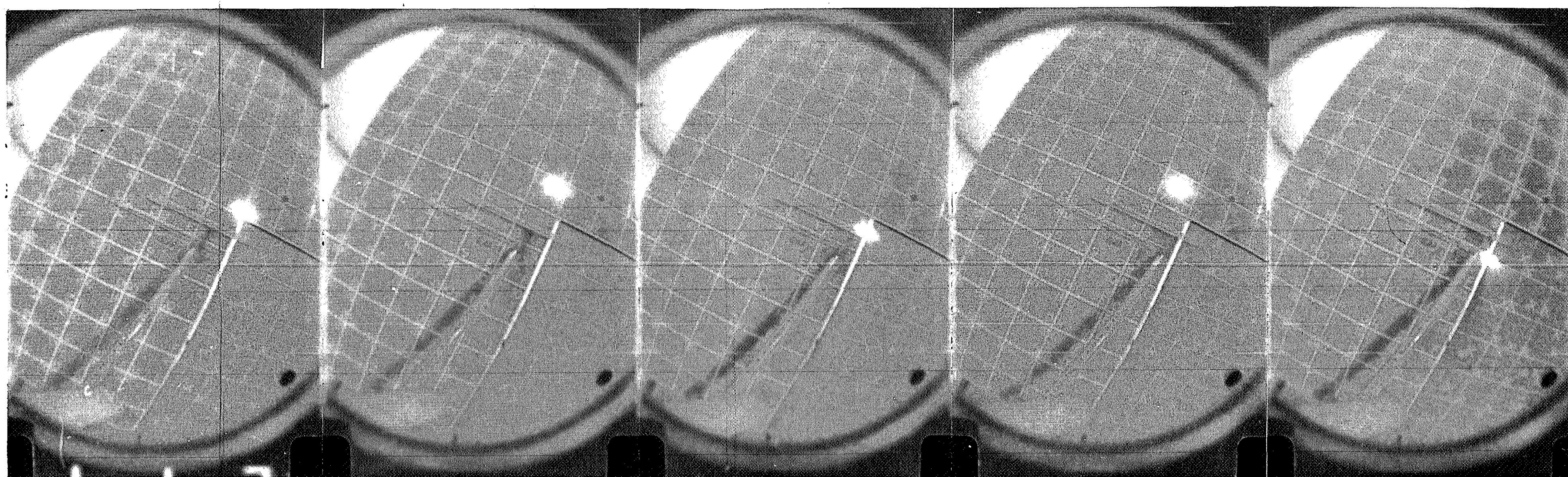

Figure C-4. Eye-Motion Camera Calibration Film

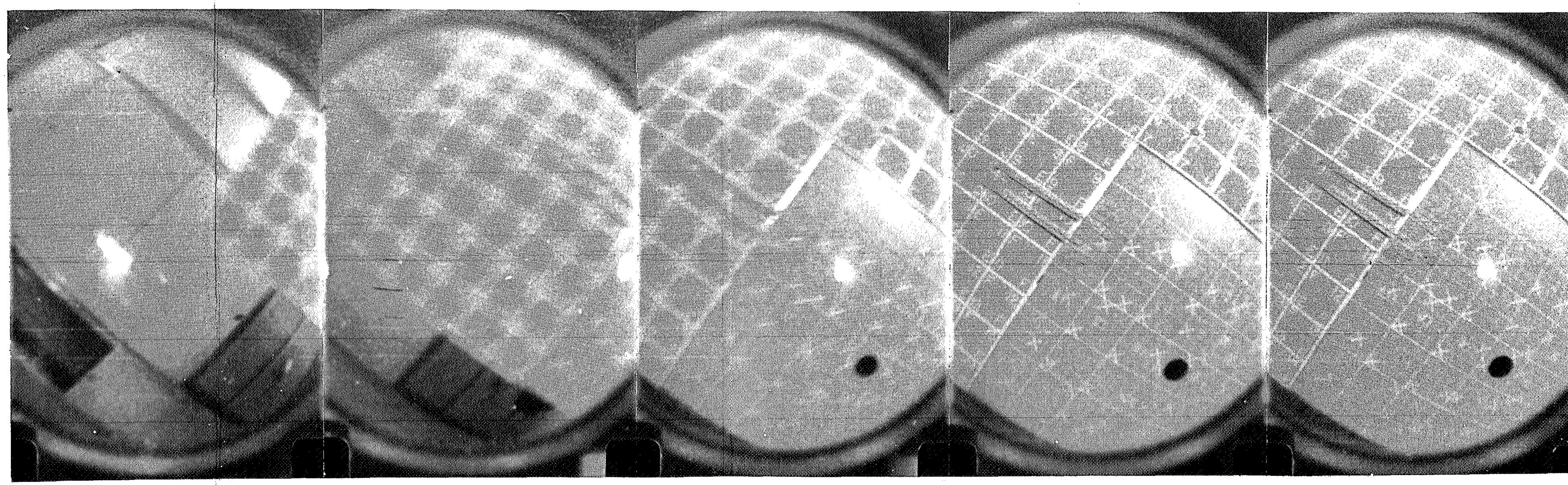

Figure C-5. Eye-Motion Camera Head Turn Film illumination, using Eastman 4-X Type 7224 film, at f16, and 16 f/s. Viewing from left to right: eye movement from frame one (letter D) to frame two (RATER display) is 3°, from frame two to frame three (letter E) is 6°, and from frame four (RATER display) to frame five (letter F) is 9°. Diameter of entire field of regard is approximately 40° of visual angle. Calibration grid squares measure one inch on a side.

A complete calibration sequence was run at the beginning of each Y-axis group of sequences and at the beginning of each Z-axis group. The subject would not alter his position throughout a given group of sequences. However, as a reliability safeguard, a calibration leader was spliced in front of each 100-foot roll of film and a check made before each sequence to assure the eye spot's being sharply centered and focused.

During actual test sequences, film footage precluded running the camera continuously; therefore, control timing circuitry was programmed to start the camera a few seconds before each trial started and to stop it a few seconds after it ended. After each sequence the on-board examiner would unload the exposed film, reload the camera, and change the position of the test chair for the next sequence. As in Experiment 1 of Task II, the head turn for all orientations was 70° and the RATER was operated on the self-paced mode with the same button-color control-display combinations. The collimation index was also unchanged, providing a 1° visual display.

Figure C-5 is a representative excerpt from a head turn test film (subject G.T. in the Z_{90} orientation), photographed with normal room illumination, using Eastman 4-X Type 7224 film, at f11, and 16 f/s. Viewing from left to right and counting frames from the beginning of the subject's head turn: the first picture is the second frame (2f), the second picture shows the eye spot about to disappear at right margin of camera field (5f), the eye spot has reappeared in the third picture (17f), and the fourth (20f) and fifth (23f) pictures show a stable field of regard but a 3° movement of eye spot.

Although Figures C-4 and C-5 are positive prints, test films were ordinarily processed and analyzed as negative. Figure C-6 depicts a frame-by-frame analysis being made of a test film, using a Vanguard Model M16-10(15X) Motion Analyzer. The first step in data analysis produced a series of single sheets of

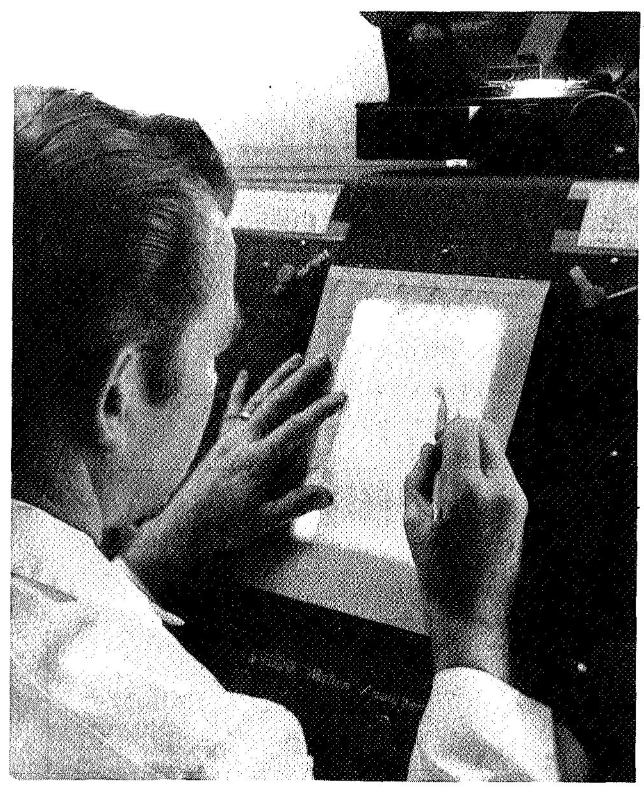

Figure C-6. Test Film Motion Analyzer

tracing paper, each bearing a complete record of the absolute eye spot movement during a single trial of a single subject. Figure C-7 shows a close-up of the single frame display, Figure C-8 the same frame with superimposed Interchem tracing paper bearing a locus of points duplicating the eye spot positions in preceding frames.

To isolate evidence of modal phenomena, specifically "past-looking" resulting from eye movement (LEM), eye movement loci for a given orientation for the entire sample of subjects were collected on one chart (as shown in Figures C-9A through C-9C) by embossing the separate loci from the separate sheets and determining the coordinate mean for each frame of the trial.

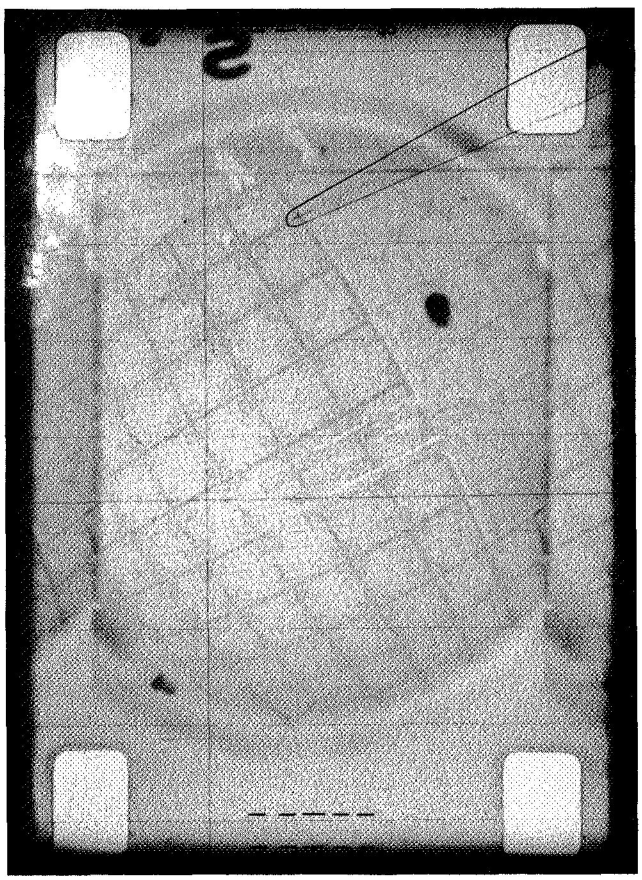

Figure C-7. Single Frame Display

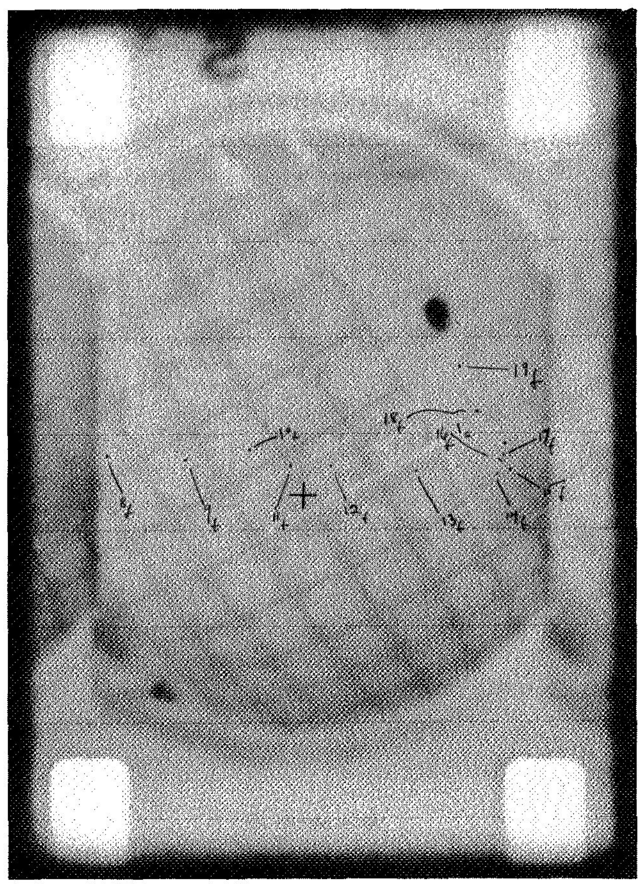

Figure C-8. Locus of Eye Spot Position

NOTE

Film speed was 16 frames/second.
Frames (f) and seconds (s) indicate
from beginning of subject's head turn.

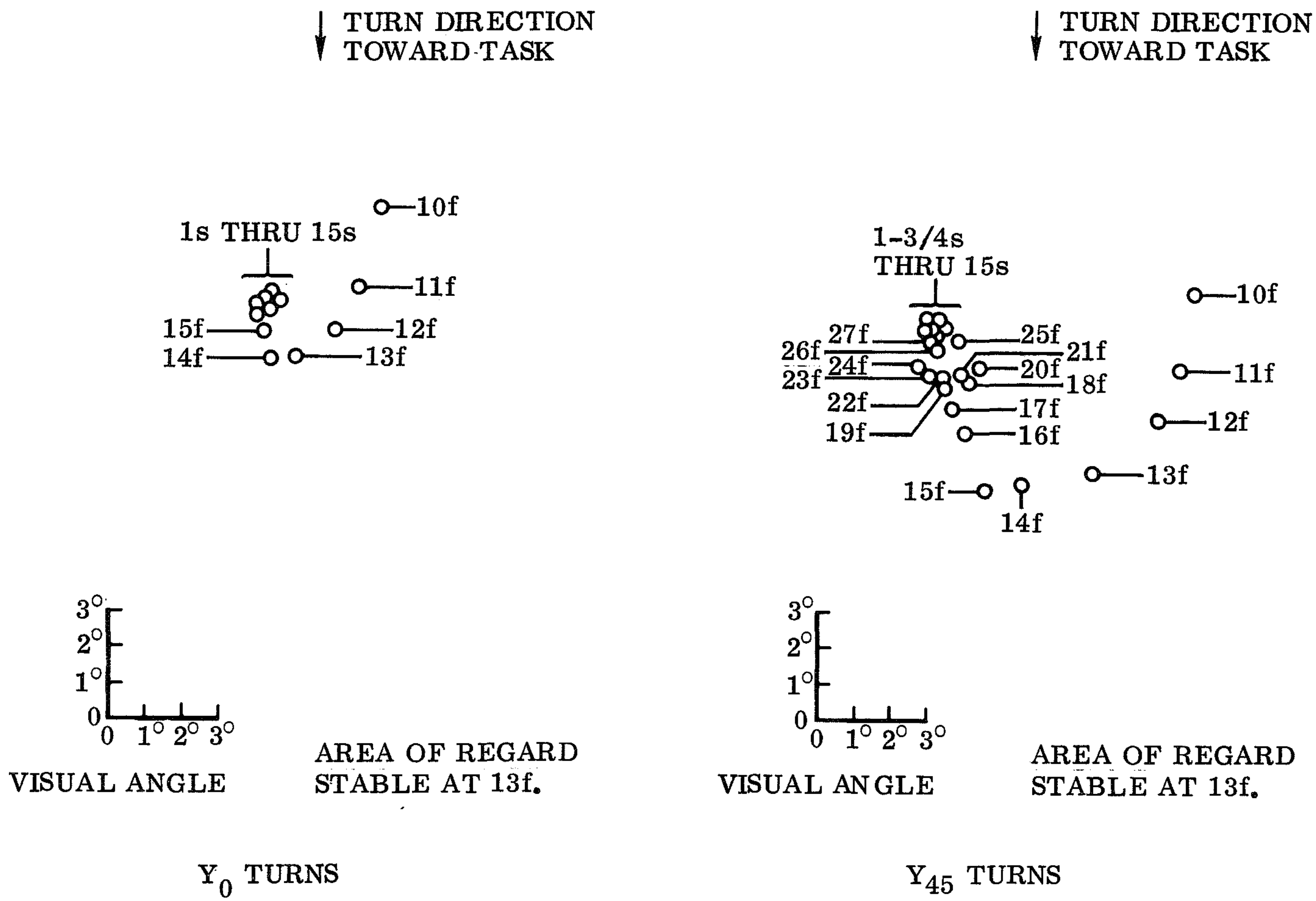

Figure C-9A. Composite Oculograms for 8 Subjects (Plotted from Eye-Motion Camera Film For Y_0 and Y_{45})

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NOTE

Film speed was 16 frames/second.
Frames (f) and seconds (s) indicate
from beginning of subject's head turn.

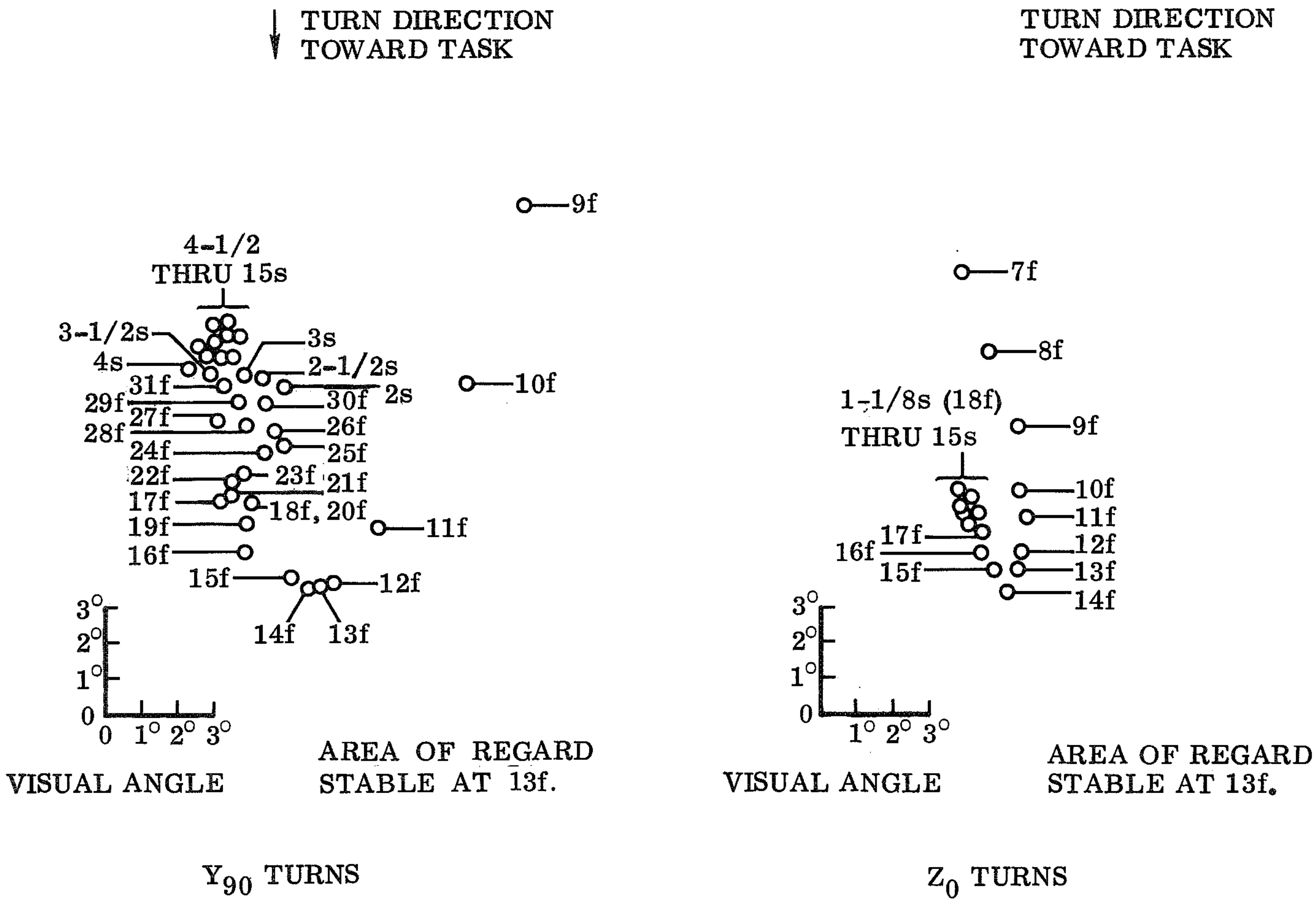
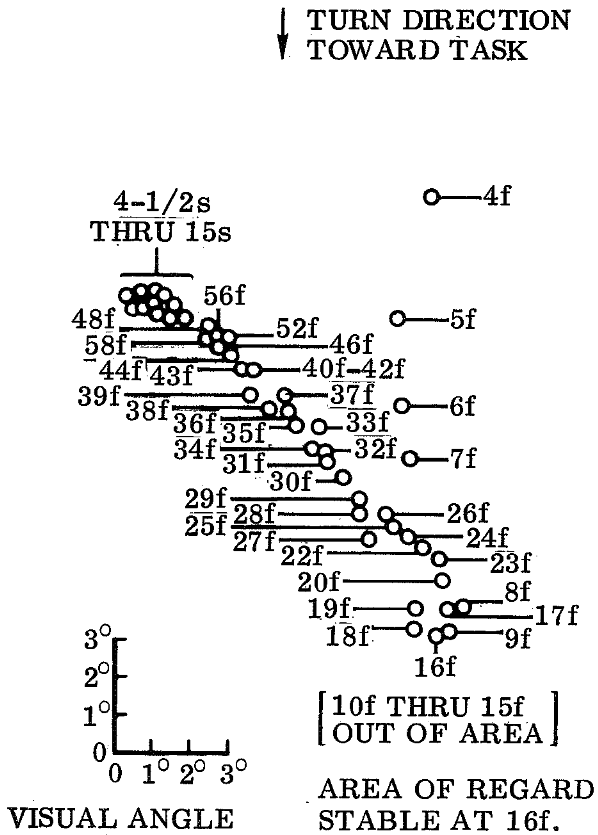


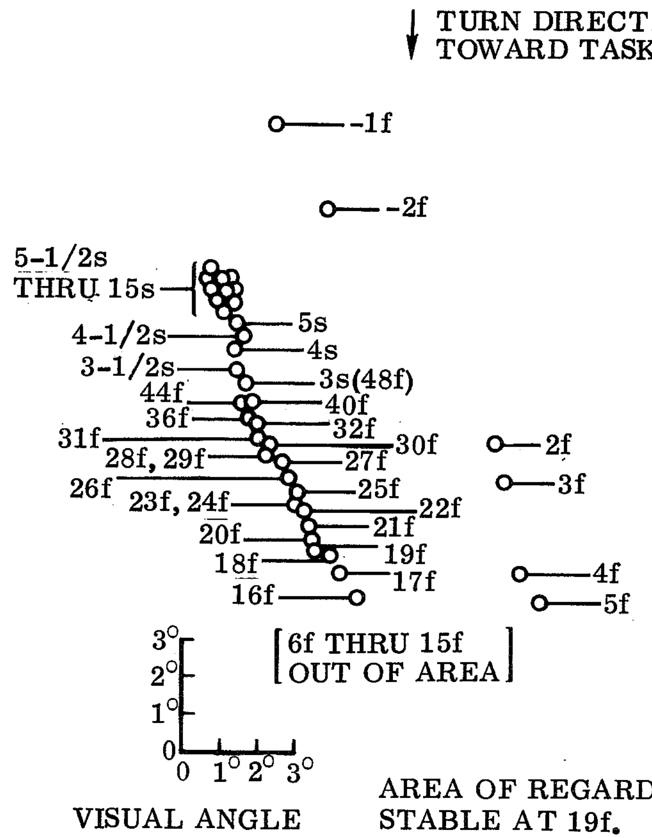
Figure C-9B. Composite Oculograms for 8 Subjects (Plotted from Eye-Motion Camera Film For Y_{90} and Z_0)

NOTE

Film speed was 16 frames/second.
Frames (f) and seconds (s) indicate
from beginning of subject's head turn.



Z_{45} TURNS



Z_{90} TURNS

Figure C-9C. Composite Oculograms for 8 Subjects (Plotted from Eye-Motion Camera Film For Z_{45} and Z_{90})

APPENDIX D

NARRATION FOR FILM PREPARED UNDER THIS STUDY CONTRACT

APPENDIX D

NARRATION FOR FILM PREPARED UNDER THIS STUDY CONTRACT

A subject seated in a 45° inclined chair placed in the Convair Manned Revolving Space Station Simulator (MRSSS shown in Figure D-1) spinning at 12.2 rpm and inclined at 45° can be oriented so the plane of head rotation about either the Y or Z axis has any desired angle of inclination to the plane of spin being swept out by the rotating centrifuge arm. For this study the chair was oriented so subjects performed perceptual-motor tasks requiring Y and Z axis head rotations either parallel, perpendicular, or at 45° inclination to the plane of spin. Resultant acceleration from gravity and centrifugal vectors was normal to the floor, so the angle between the axis of the otolith and the resultant vector was the same for all experimental positions. Variation in performance scores on the perceptual-motor task in these orientations indicated which position and type of head rotation was least disturbing to the performance task and which caused the least physiological reaction.

A plastic model (Figure D-2), demonstrates the scheme used to align the resultant acceleration so the effects of head turns in planes at various angles out of the plane of spin can be investigated using perceptual motor tests as criteria of performance

Nodding motions of the head are referred to as Y-axis motions and side-to-side turns as Z-axis head turns. The subject is seated in a chair inclined 45° to its left side. With the floor inclined at 45°, the subject's spine can then be positioned at any angle from 0° to 90° to the spin plane of the simulator. In all positions, the subject's Z-axis is 45° to the apparent vertical within the simulator. With the subject inclined

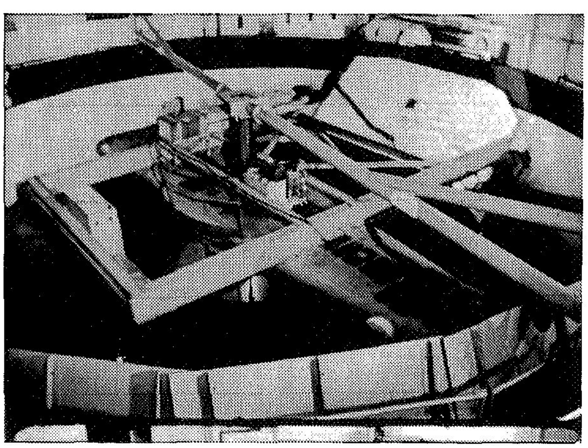


Figure D-1. Manned Revolving Space Station Simulator (MRSSS) - Spinning

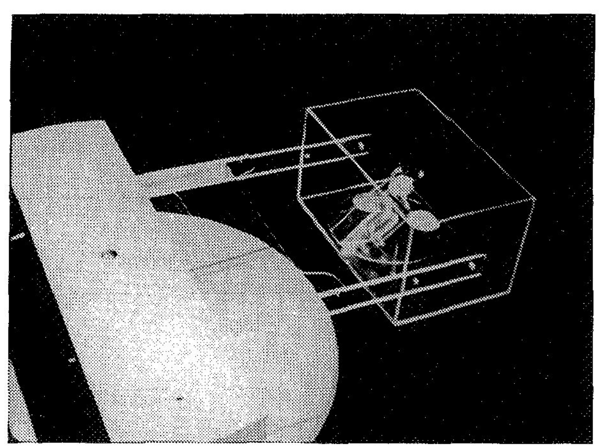


Figure D-2. Model Static, Zero-Inclination

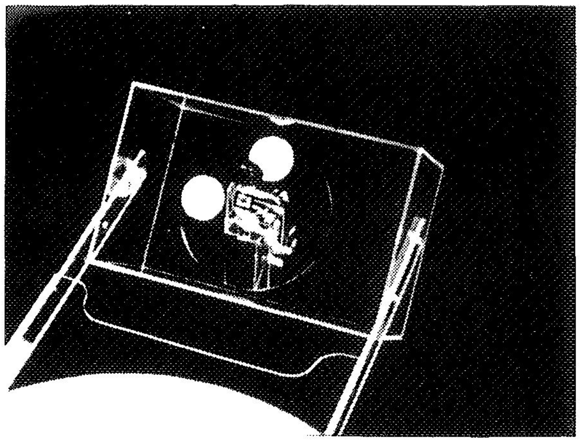


Figure D-3. Inclination of the Subject to the Outboard Side for Z_0, Y_{90}

to the outboard side of the cabin (as shown in Figure D-3), Y-axis (nodding) head turns are 90° from the spin plane and Z-axis turns are in the plane of spin; the spine is now at a right angle to the plane of spin.

When the chair and subject are rotated 90° so his inclination is toward or away from the leading bulkhead (as shown in Figure D-4), both Z and Y head turn-planes intersect the plane of spin at 45°. The subject's spine also makes a 45° angle with the plane of spin and, as always in the experiment, the subject is displaced 45° from the apparent vertical (resultant accelerations) within the room.

Inclining the chair toward the center of rotation aligns the Y axis (nodding) turns so that their plane of motion is now in the spin plane and Z axis turns are at right angles to the spin plane. Theoretically, the greatest disorientation should result from head motions performed at right angles to the plane of spin. Figure D-5 shows the subject with his spine aligned in the plane of spin.

With this experimental design, it is possible to place the man at various angles to the plane of spin. In the operational space station, the standing astronaut's spine will be in the plane of spin; head turns about the Z axis (side to side) will be 90° out of that

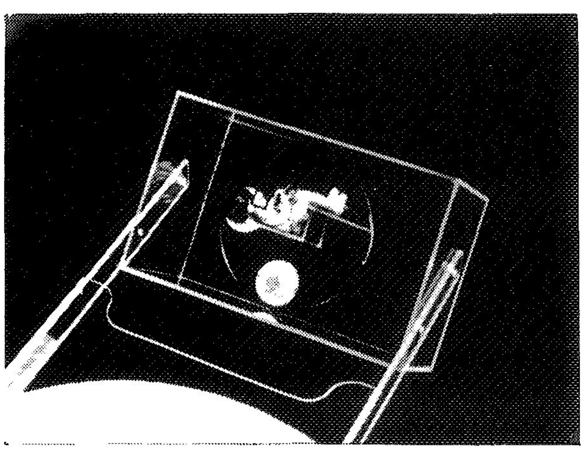


Figure D-4. Subject Inclination Toward Trailing or Leading Bulkhead for Y_{45}, Z_{45} Interplanar Angles

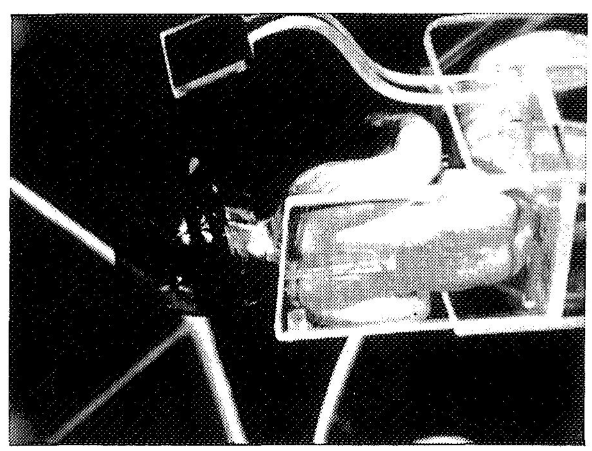


Figure D-5. Subject Inclination Toward the Center of Rotation for Z_{90}, Y_0 Interplanar Angles plane but the Y axis turns can be from zero to ninety degrees, or from what should be minimum to the maximum for disorientation. This study compares the performance degradation following these various angles of head turns in order to learn more about the way displays and controls should be laid out.

The chair used for all experiments is mounted so it turns about a point below the head. The restraint arrangement (shown in Figure D-6) fixes the subject's head so he can move only in the designated plane through a 70° arc. Head position is recorded remotely by potentiometers attached to both Z and Y axes. Adjustment for the large anthropometric differences among subjects is possible so the head turns are performed naturally. Task I makes use of the "Logical Inference Tester" to determine the effect of head turn on performance. Twenty buttons must be pressed in the correct order to light all buttons. A correct response turns off all lights that follow it in the programmed sequence, indicating mistakes (buttons pressed out-of-sequence).

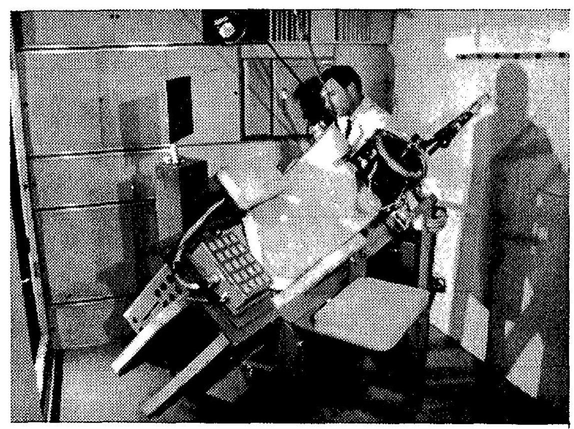


Figure D-6. Inclined Chair with Head Restraint, Signal Light, and Performance Tester

A collimated signal light initiates the head turn for either the Z or Y axis. The signal is set so the subject makes a natural head turn through 70° to perform the task. Variation in mode of head turn, as well as anatomical differences in subjects, require that the axis of turn for both Y and Z have adjustments in the three orthogonal planes. This is particularly true for the Y axis, since the motion involves the cervical vertebrae to variable extents, and this shifts the axis of rotation.

The subject's console for the LOGIT is mounted either in the subject's lap or on his right. Both positions have adjustments that allow the entire panel to be reached easily without requiring the elbow to be lifted from the support. Vertical adjustment is provided by a heavy duty camera tripod mount. The subject is first seated and the restraint system adjusted to his dimensions so the head turn is natural; next the LOGIT is positioned for easy reach, and finally the signal light positioned to require a 70° head turn on signal. The subject was tested ten times in each orientation. Each trial was 15 seconds; trials were separated by 20 seconds of rest while waiting for the signal light to appear.

Figure D-6 shows the position of the LOGIT and cue light for Y-axis testing. When the signal appears, the subject makes a head turn as quickly as possible toward the console and commences the test, pushing as many of the buttons in order as possible. Following ten such trials and rest periods, the chair is rotated to a new orientation and the test is repeated. When the Y_{90}, Y_{45}, and Y_0 orientations are completed, the room is brought back to zero rpm and the apparatus is readjusted to permit testing in the Z-axis orientation. Accumulative effects were nulled out by balancing permutations of orientation sequences.

Eye motion was evaluated with oculograms in Task I but the large surface of the LOGIT console required considerable eye scanning. The first experiment of Task II repeated the previous head turns but the task was changed. A performance tester known as the Response Analysis Tester (RATER) was used so the subject could focus on a single point of light, as shown in Figure D-7. The light was one of four colors; each color corresponded to a button. The test required response to the color by pressing the correct button — a new color then appeared. The score was the number of correct responses minus the errors. The colored light was collimated and presented one degree of visual angle. The angle of head turn was once again through 70° of arc, required by location of the signal light. Eye movements were recorded as horizontal and vertical electro-oculograms. Possible degradation in performance due to the action of inertial forces on the fingers was eliminated by placing the response buttons in the lap and restricting finger movement to a simple pressing motion.

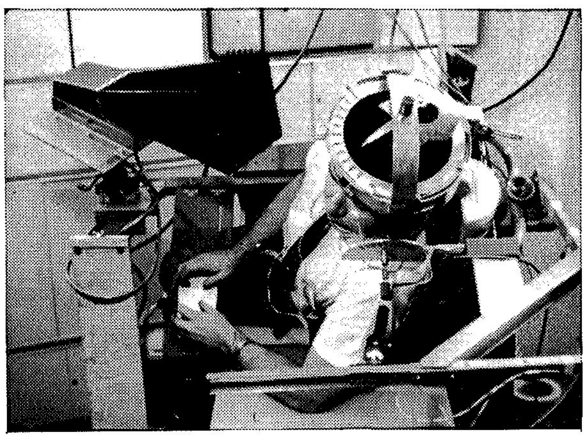


Figure D-7. Rater Test and Point Display Used for Nystagmus Recording

These tasks were performed for both the Y and Z head-turn axes in all orientations previously described. Performance scores correlate positively with Task I results. The oculograms demonstrated that nystagmus was occurring during performance of the tests but also indicated a gross eye movement at some orientations, indicative of searching or "past looking." Because some subjects described difficulty in "focusing" on the display, experiment 2 of Task II was done to photograph the eye and obtain direct evidence that this difficulty in looking at the target was part of the mechanism involved in performance degradation.

An eye camera was modified, as shown in Figure D-8, so it could be included on the head restraint system. While the subject is looking at a fixed point on a grid, a light spot is reflected off the cornea onto the back side of the motion picture film. The camera simultaneously photographs this spot and the grid area regarded. Calibration accomplished prior to the test makes it possible, by means of the reflected light spot, to determine what the subject is looking at on the scene (grid) being photographed. The RATER display was incorporated with the grid and the experiment of Task II, Experiment 1, was repeated.

The camera was kept in a constant position with respect to the eyes by means of a bite bar. A dental impression was made for each subject and used to completely fix the camera position with respect to the skull. Because focusing of the light spot is so critical, the point was checked between each orientation, which required a return to the static position. This also allowed for the changing of film and any other adjustment that might be necessary. The film in the camera was started just prior to the signal light and continued until the trial was completed.

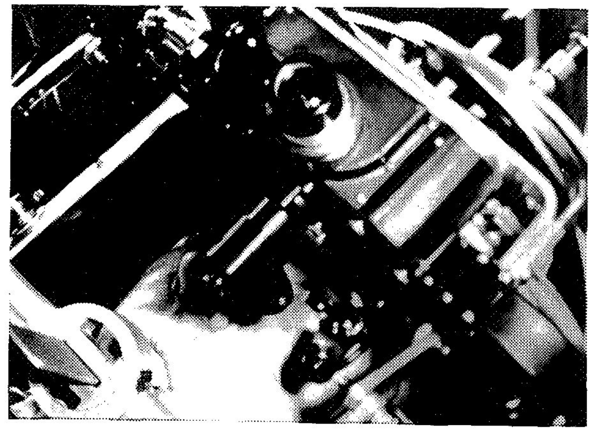


Figure D-8. Eye Camera Used to Study Gross Eye Movements Resulting from Head Turns in the Rotating Environment

The photograph (Figure D-9) shows the results of a Y-axis turn. The spot is the reflected spot from the cornea (first Purkinje image) superimposed on the grid. By previous calibration, the point of gaze can be plotted for each frame of film.

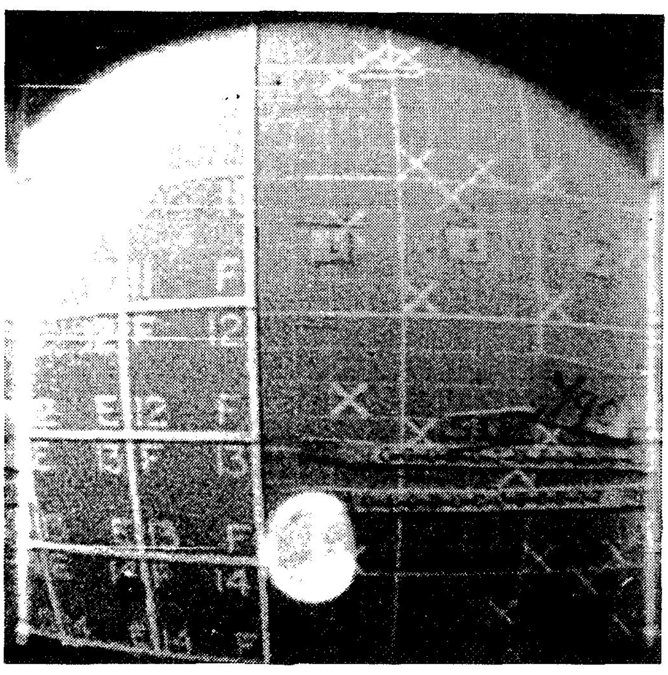


Figure D-9. The Reflected Light Spot Superimposed on the Grid Was Used to Determine Where the Subject Was Looking

To determine how control operation might be affected by arrangement of displays to permit Y_0 head turns to be used for monitoring, a reach experiment was performed. The RATER display was used again. This time the subject's head was restrained from all movement. The display was placed in front of his eyes and the buttons were fixed on a bar. The response buttons could be arranged to the reach requirement over a 12-, 24-, or 36-inch distance. The bar rotated so the vertical reach could be compared to the horizontal. The test arrangement is shown in Figure D-10. Theoretically, the vertical reach, which is a radial motion in the space station, should be subject to coriolis deflection. Horizontal reach, being a motion parallel to the axis of rotation, should have

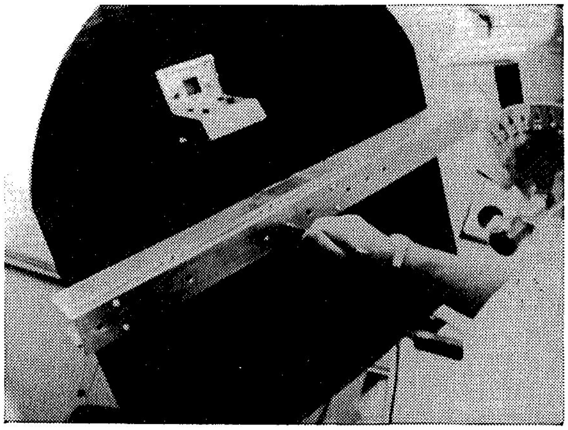


Figure D-10. Coriolis Deflection of the Arm Was Studied by Comparing Horizontal and Vertical Control Arrangements.

the least deflection. Since no difference in horizontal and vertical arrangement was observed when the subject depressed one-inch buttons, the experiment was performed using a 1/4-inch diameter stylus to depress 3/8-inch diameter buttons; this increased test sensitivity but again revealed no decrement in either axis.

GENERAL DYNAMICS

Convair Division